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Power generation from thermal radiation: Photon-assisted tunneling in a metasurface-coupled rectifier

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Outline

- Introduction
  - Motivation:
  - Direct Conversion: Infrared Rectenna.
  - Resonant transverse field enhancement and confinement in tunnel gap.
- Electrical Power Generation from a Thermal Source[1]
  - DC electrical power generation.
  - Photothermoelectric measurement.
  - Summary
- Model for Photon-assisted Tunneling in Nanoantenna-coupled Tunnel Diode[2]
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[1] "Power Generation from a Radiative Thermal Source Using a Large-Area Infrared Rectenna", Joshua Shank, Emil A. Kadlec, Robert L. Jarecki, Andrew Starbuck, Stephen Howell, David W. Peters, and Paul S. Davids, PHYSICAL REVIEW APPLIED 9, 054040 (2018).
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- Model for Photon-assisted Tunneling in Nanoantenna-coupled Tunnel Diode[2]

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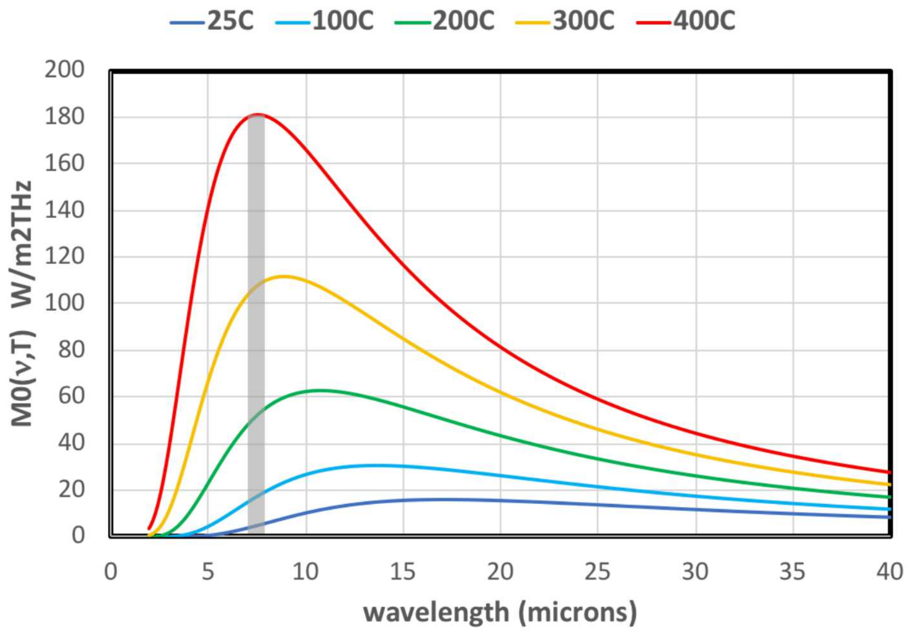
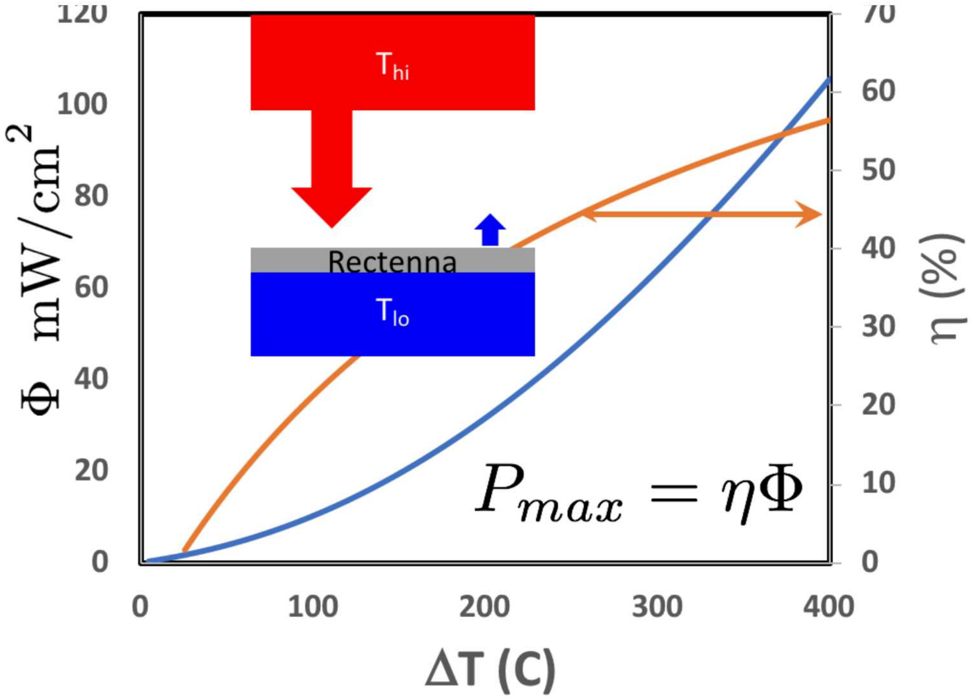
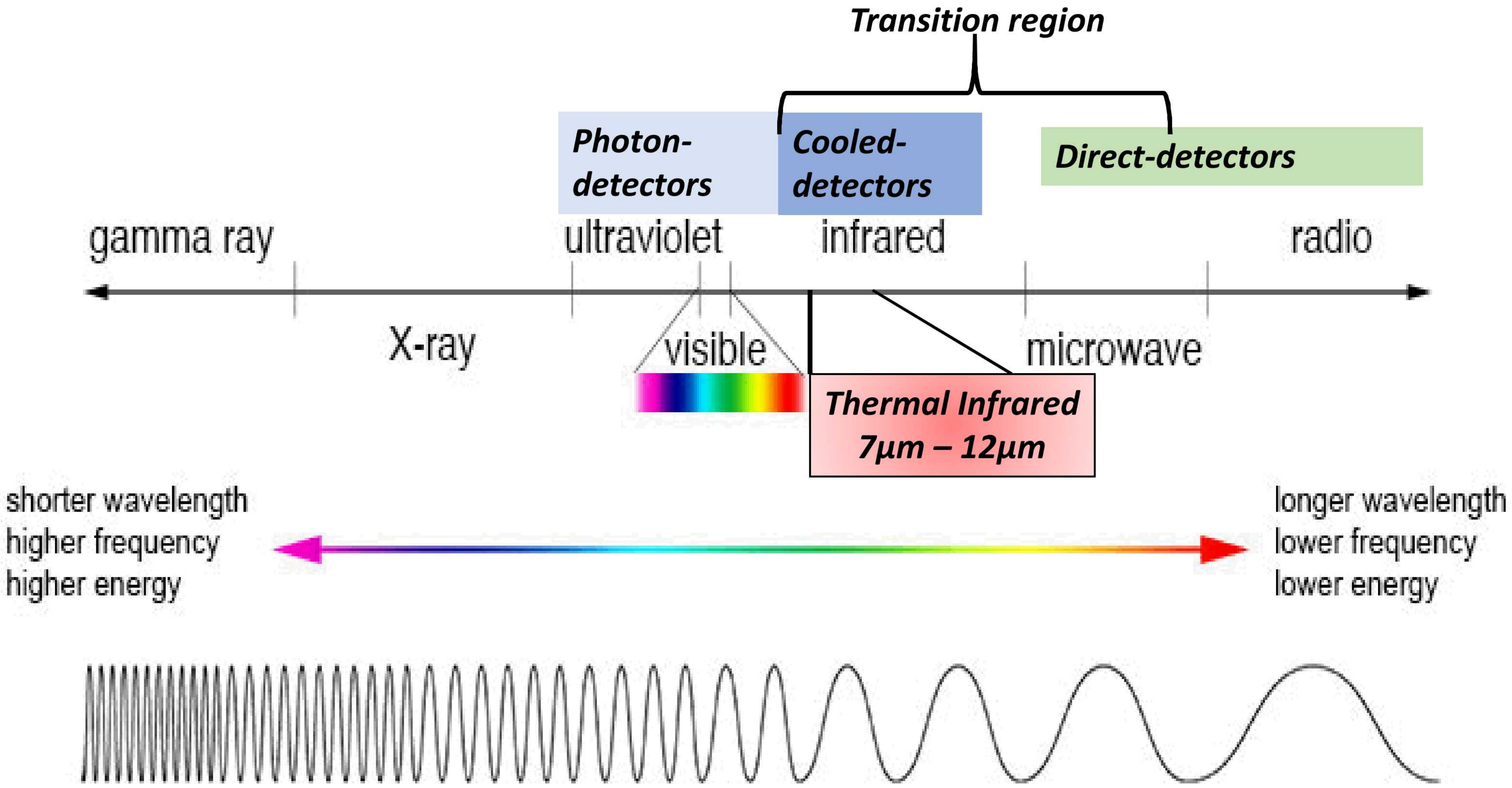
Motivation

- Thermal sources radiate as black or grey bodies with spectrum determined by their surface temperature.
- At moderate temperatures (25C - 400C), spectrum are peaked in the thermal infrared. (7-14 μm)
- ***Imagine if you could directly convert radiated waste heat into electricity efficiently and in large areas.***
  - You could power sensors and electronics or charge batteries.
  - Recover electricity from internal combustion engine exhaust or natural gas flares.
  - Power space systems (The Martian)
  - Improve PV conversion efficiency.
  - ……..

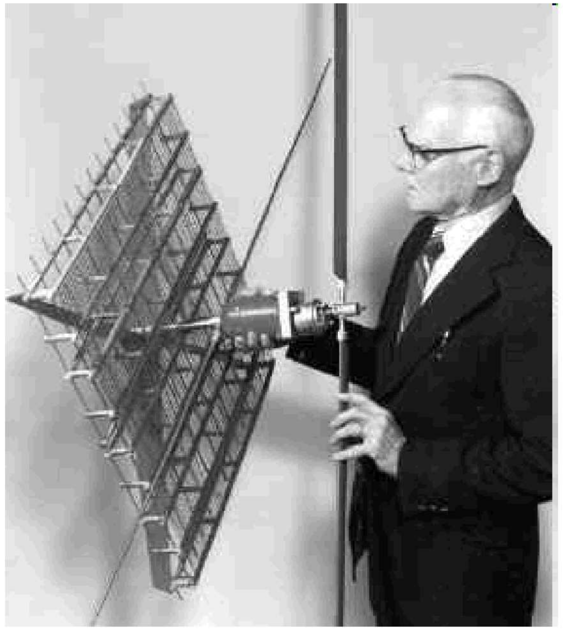




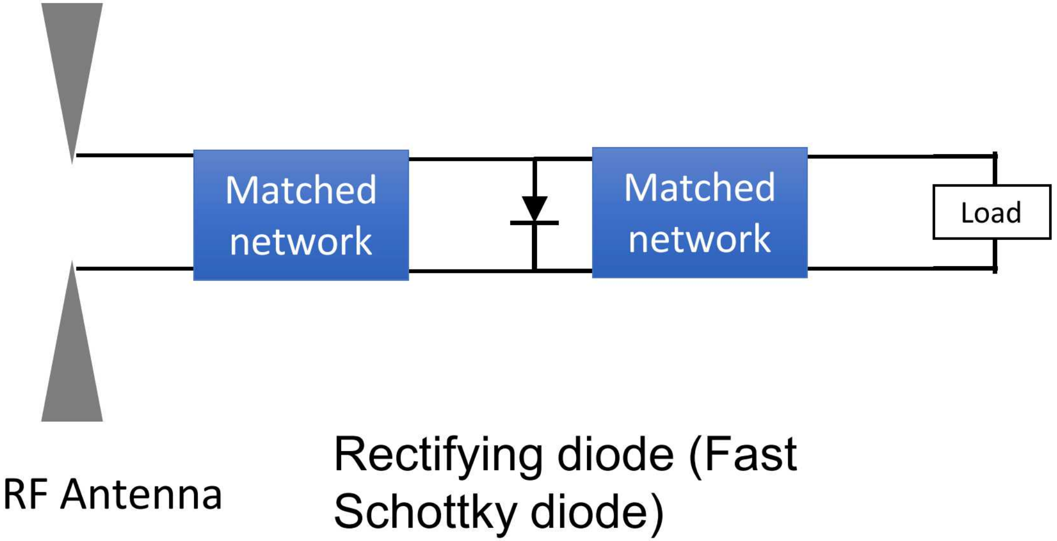
Photodetection and energy conversion



RF Rectenna & Wireless Power Transfer



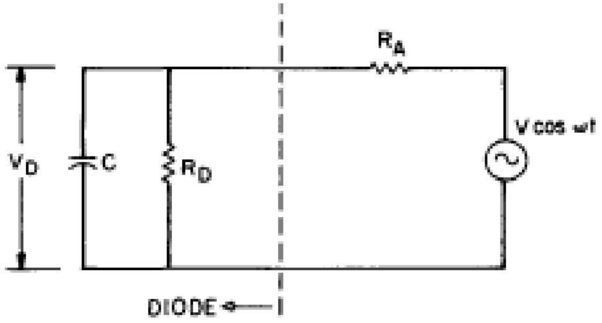
Bill Brown and RF rectenna powered helicopter.



- Rectenna (Rectifying Antenna) concept has been around since 1966 and has demonstrated direct microwave power conversion.
- Power conversion efficiency is > 85%

Can it be scaled to thermal IR spectrum and THz frequencies?

Rectifying antenna direct conversion



A. Sanchez, et. al. The mom tunneling diode: Theoretical estimate of its performance at microwave and infrared frequencies. Journal of Applied Physicss 49(10):5270–5277, 1978.

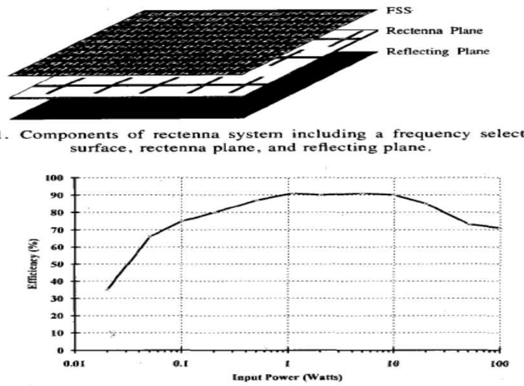
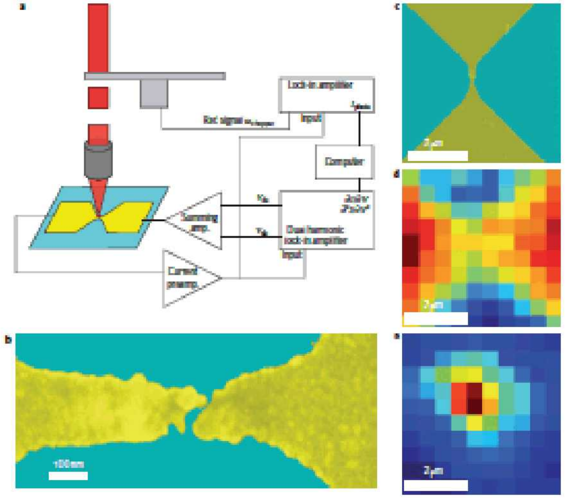


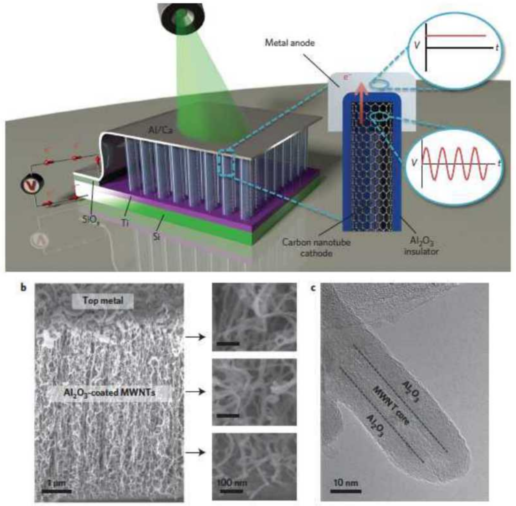
Fig. 1. Components of rectenna system including a frequency selective surface, rectenna plane, and reflecting plane.

Fig. 11. Conversion efficiency vs. input power for 2.45 GHz rectenna.

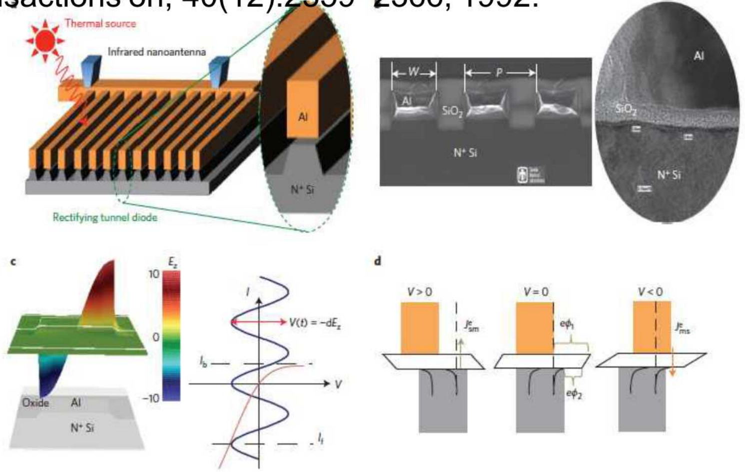
J. O. McSpadden, et. al. Theoretical and experimental investigation of a rectenna element for microwave power transmission. Microwave Theory and Techniques, IEEE Transactions on, 40(12):2359–2366, 1992.



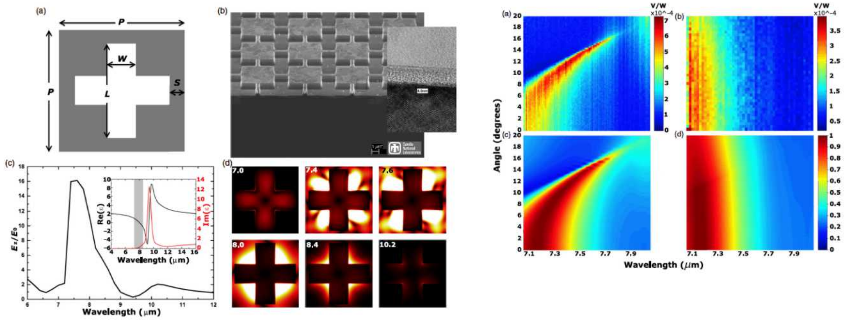
D. R. Ward, et. al. Optical rectification and field enhancement in a plasmonic nanogap. Nature Nanotechnology, 5(10):732–736, 2010.



A. Sharma, et. al. A carbon nanotube optical rectenna. Nature Nanotechnology, 10:1027 EP –, 09 2015.

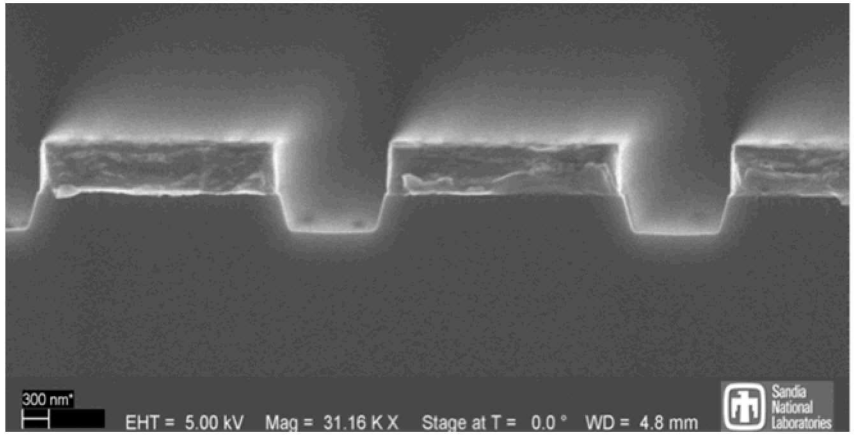


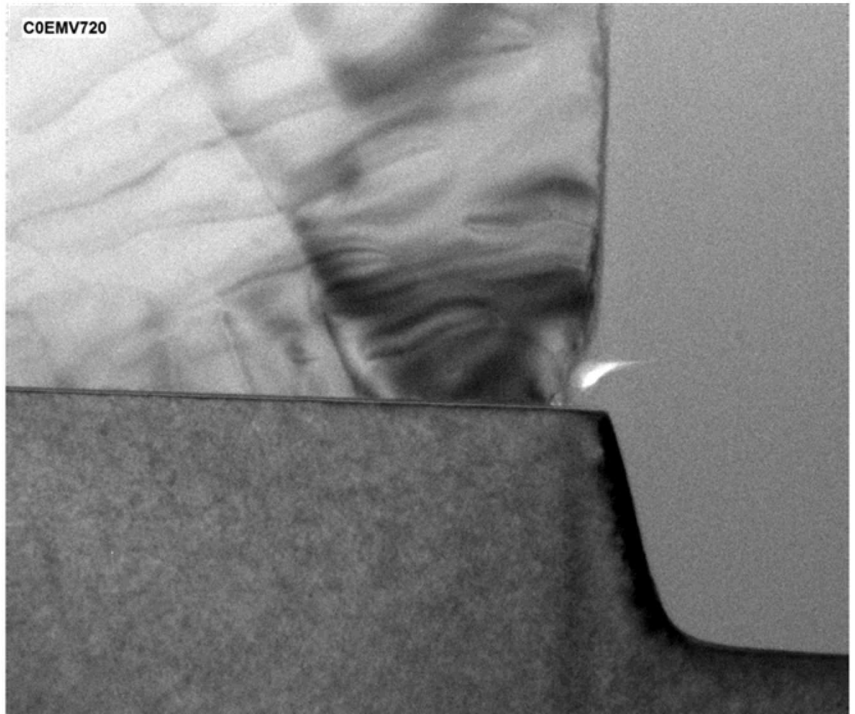
P. S. Davids, et. al. Infrared rectification in a nanoantenna-coupled metal-oxide-semiconductor tunnel diode. Nature nanotechnology, 10(12):1033, 2015.

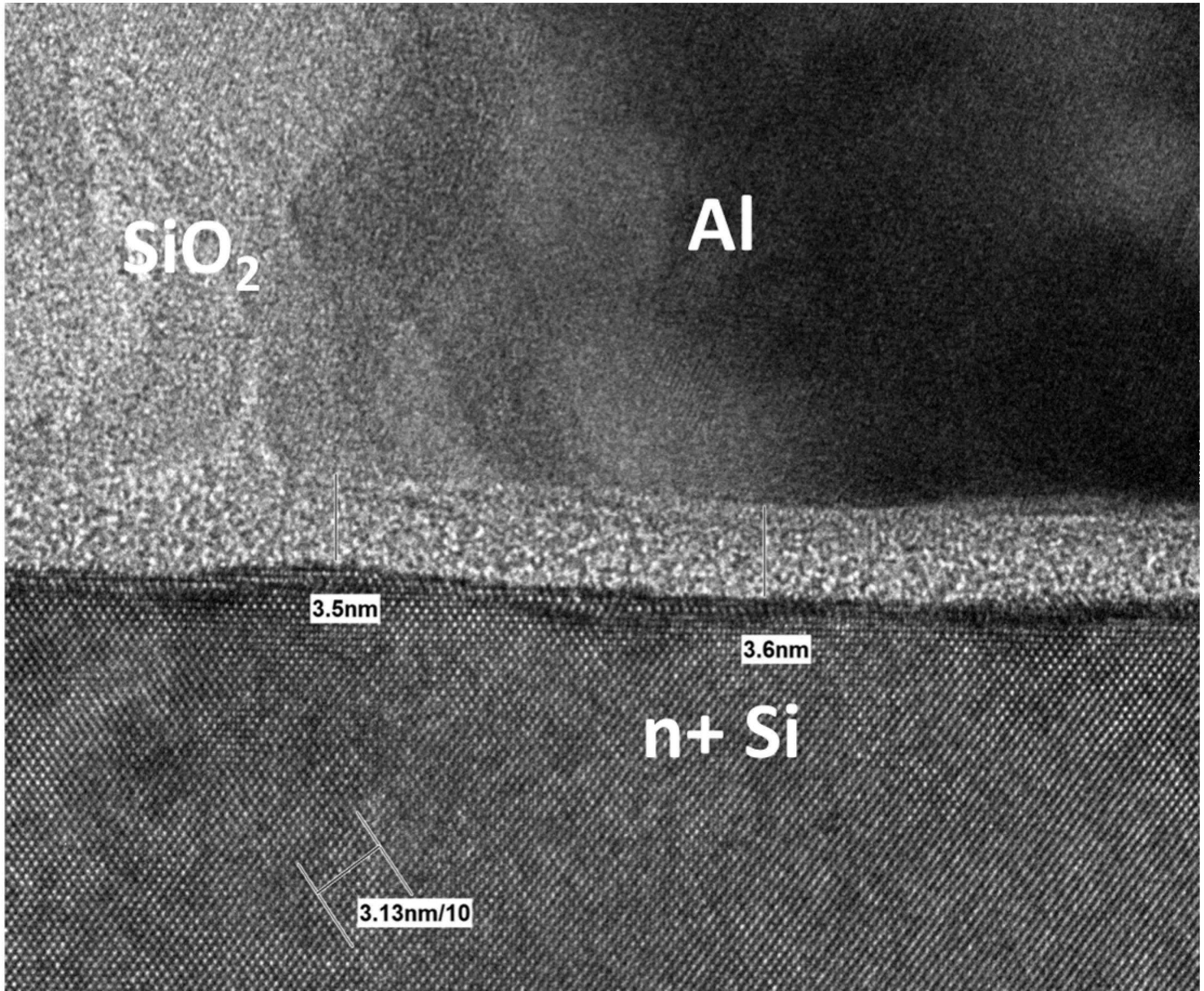


E. A. Kadlec, et. al., Photon-phonon-enhanced infrared rectification in a two-dimensional nanoantenna-coupled tunnel diode. Phys. Rev. Applied, 6:064019, Dec 2016.

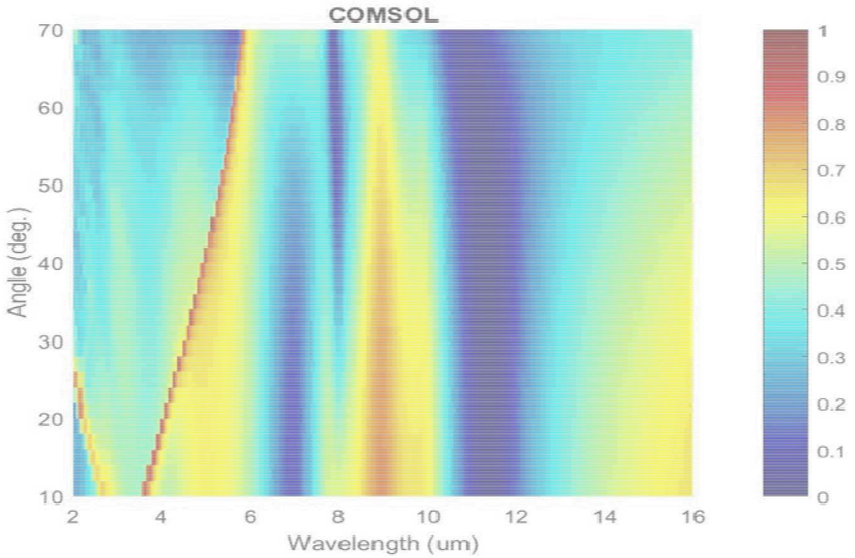
Large area 1D and 2D tunnel diode

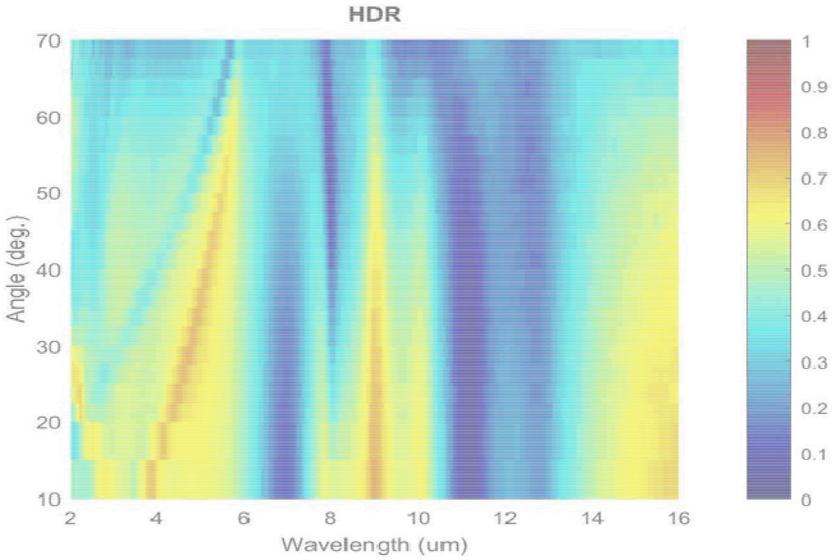


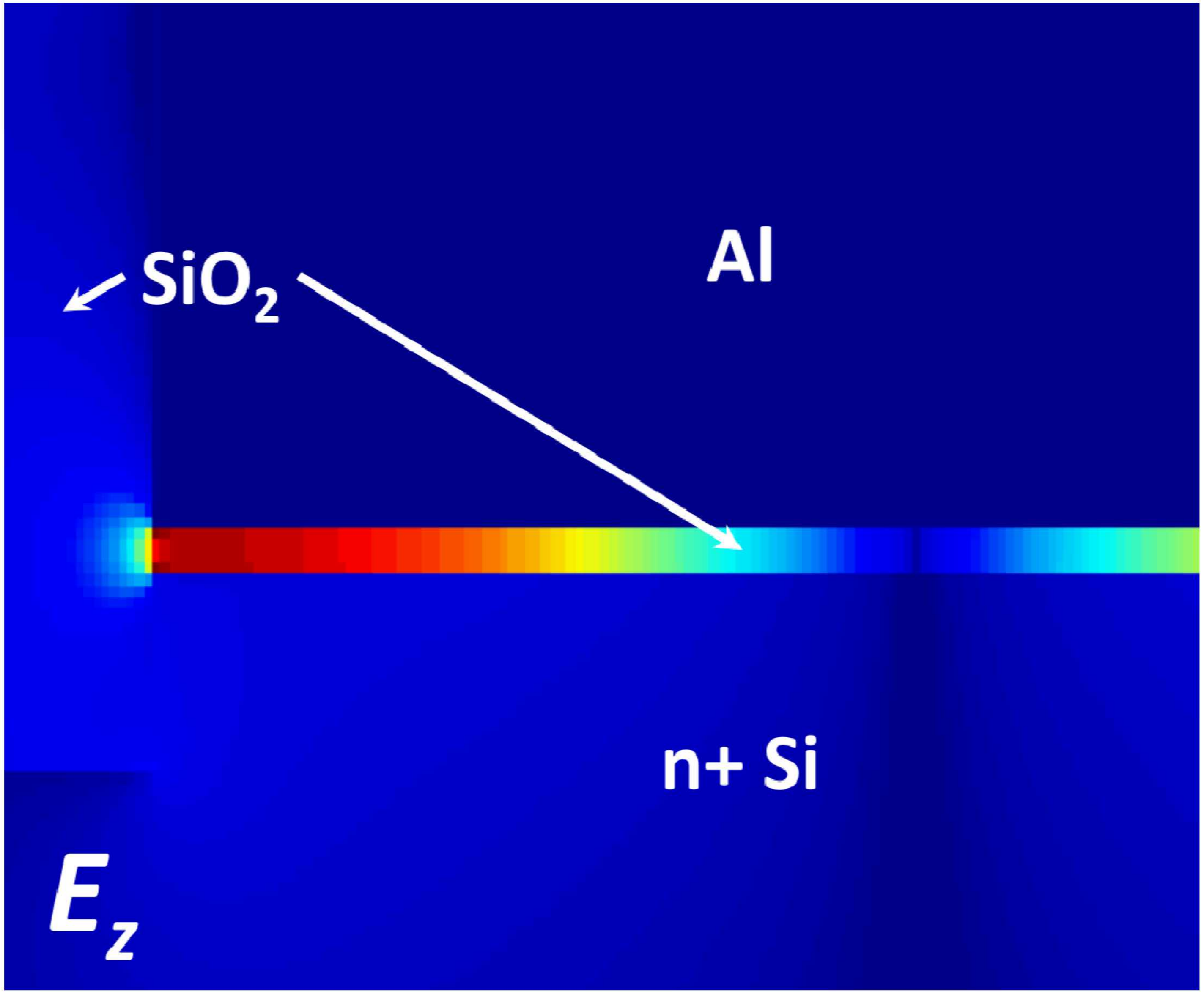




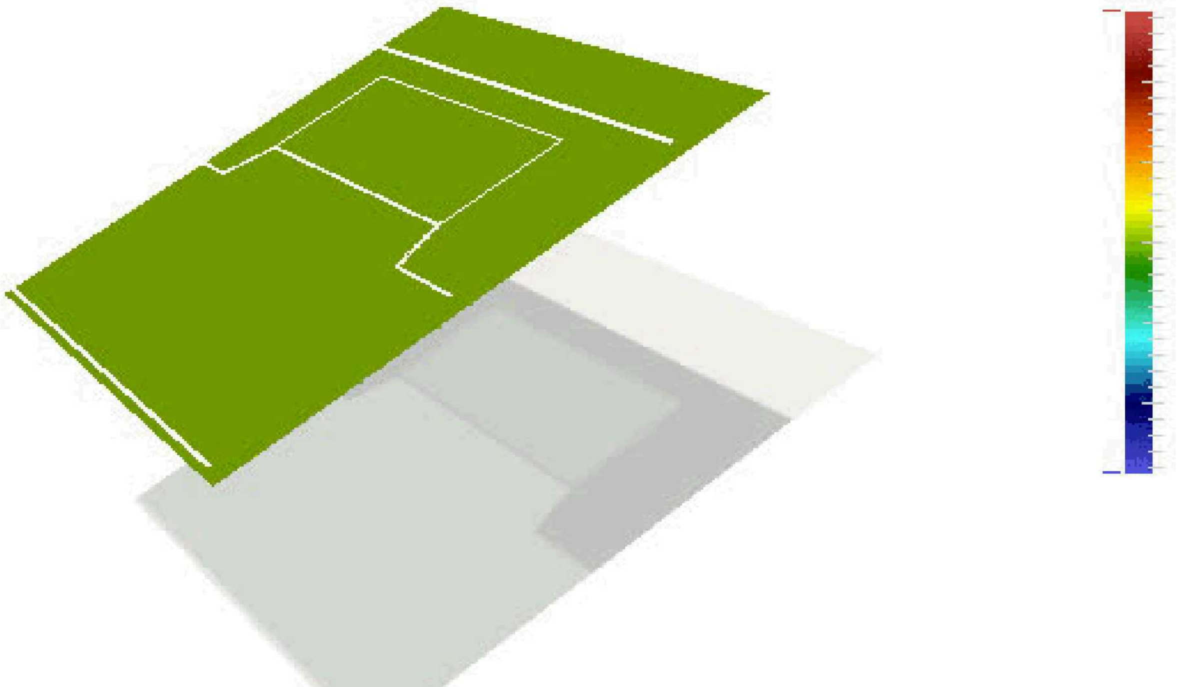
Integrated Nanoantenna-Tunnel diode







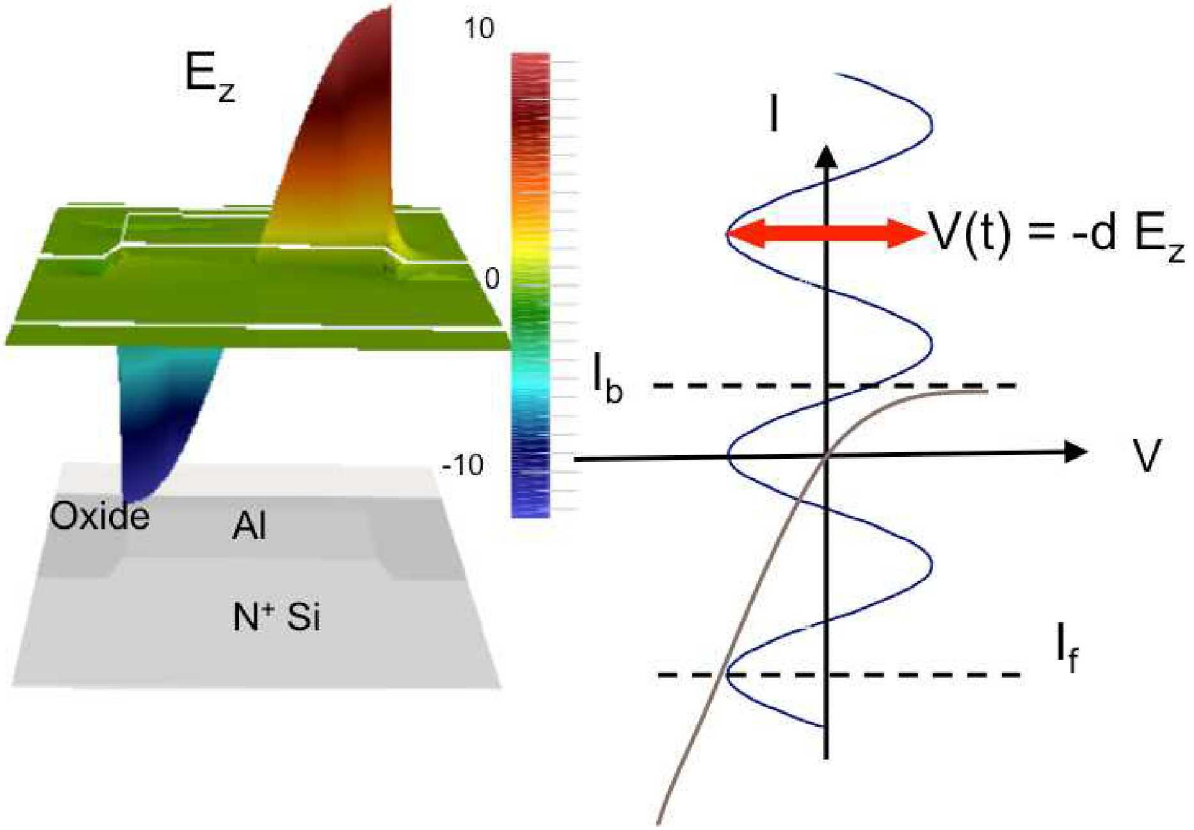
Transverse field concentration in gap



- Simulated Field enhancement in 3 nm gap is 16 x the incident field amplitude.
- Resonance occurs near epsilon-near zero (ENZ) for oxide
- ENZ for oxide is 8.1 microns
- Resonance for max transverse field is 7.3 microns.

Can intense field in tunnel barrier result in direct rectified photo-current?

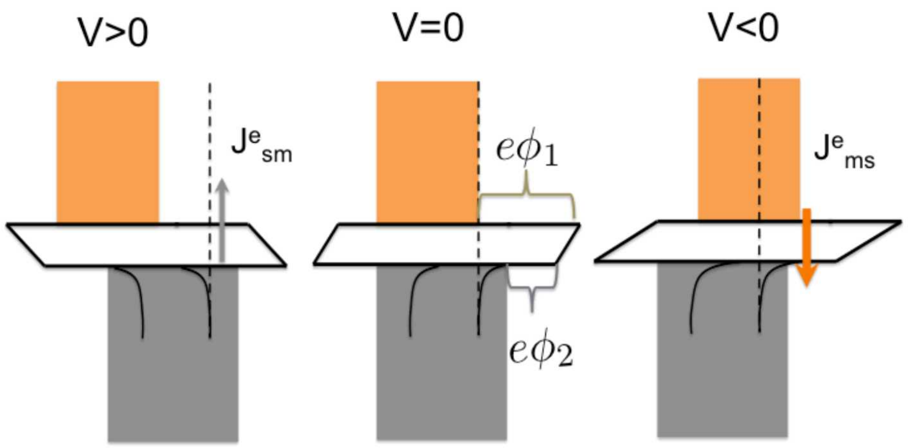
Photon-assisted Tunneling Rectification



Distributed Current in MOS Tunnel Diode

Half-wave DC current

$I_{DC} = I_f - I_b$



- Photon-assisted Tunneling current in MOS diode
- Asymmetric due to different density of states

Rectification and DC power generation

Half-wave rectifier

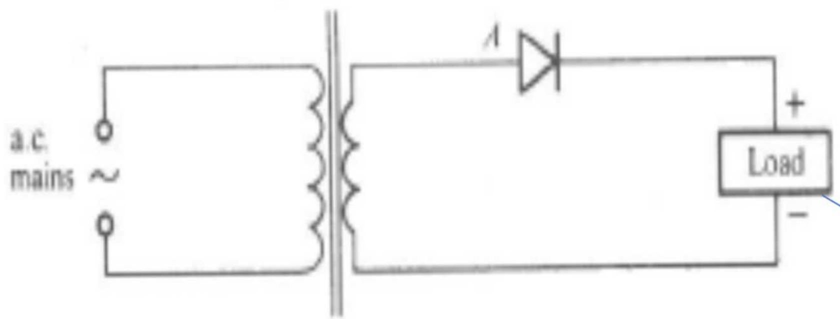


Fig. 9.1. A basic d.c. power-supply transformer and HW rectifier

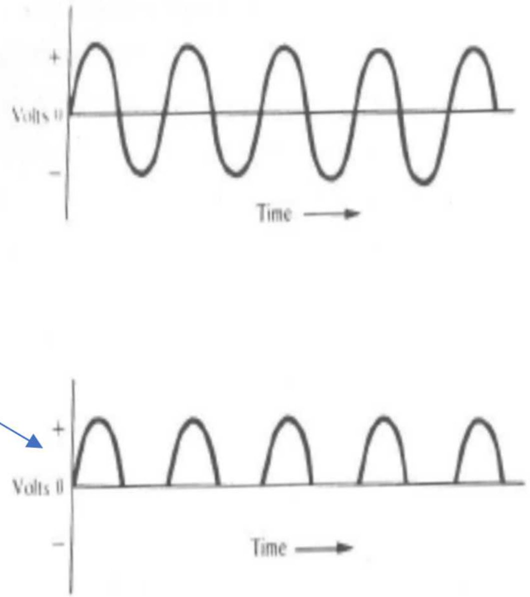
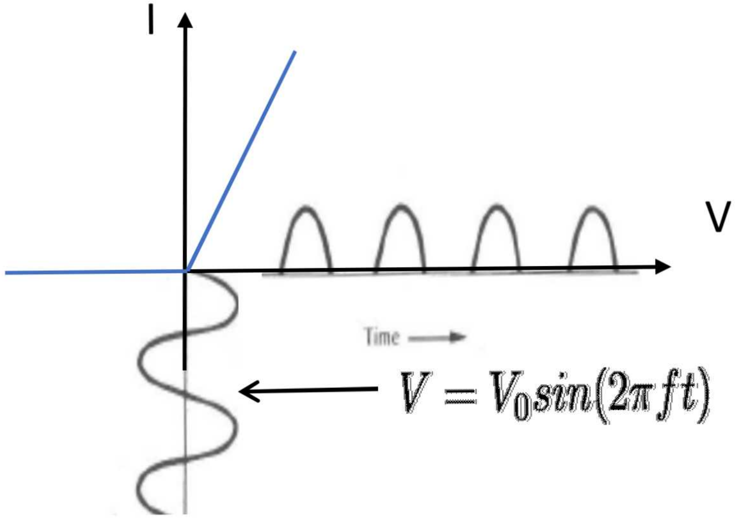
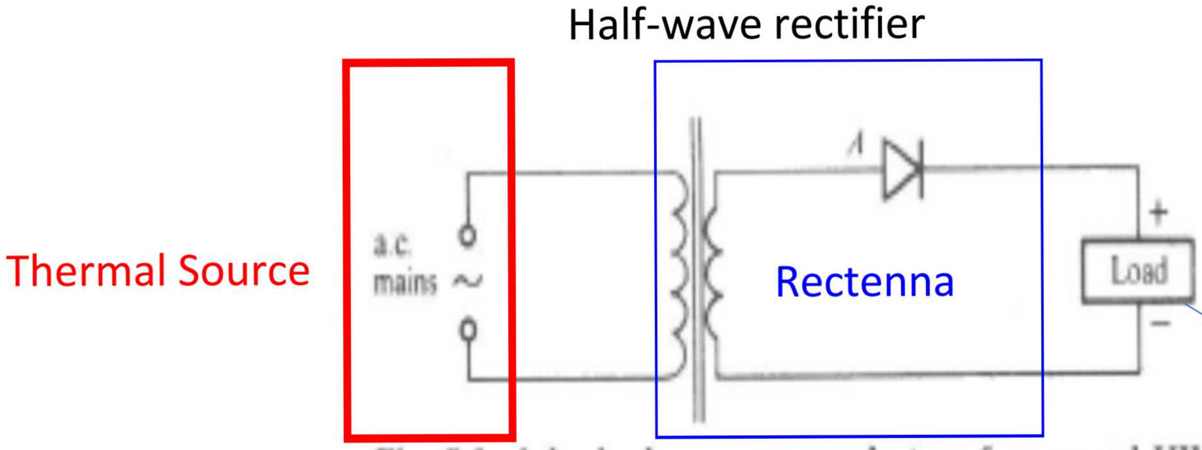


Fig. 9.2. Waveforms in HW rectifier circuit: (a) a.c. input waveform, (b) rectified unidirectional waveform across load.

Rectification in ideal diode



Infrared Rectenna Power Supply (IRPS)



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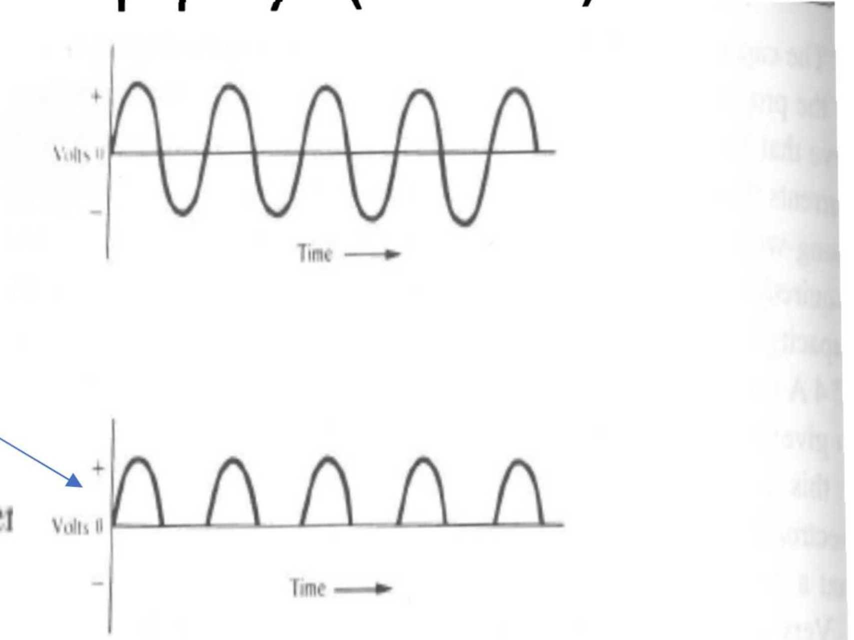

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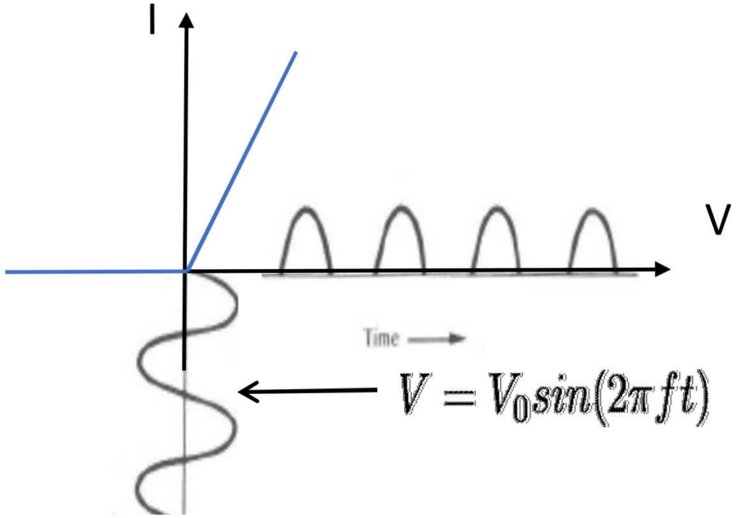
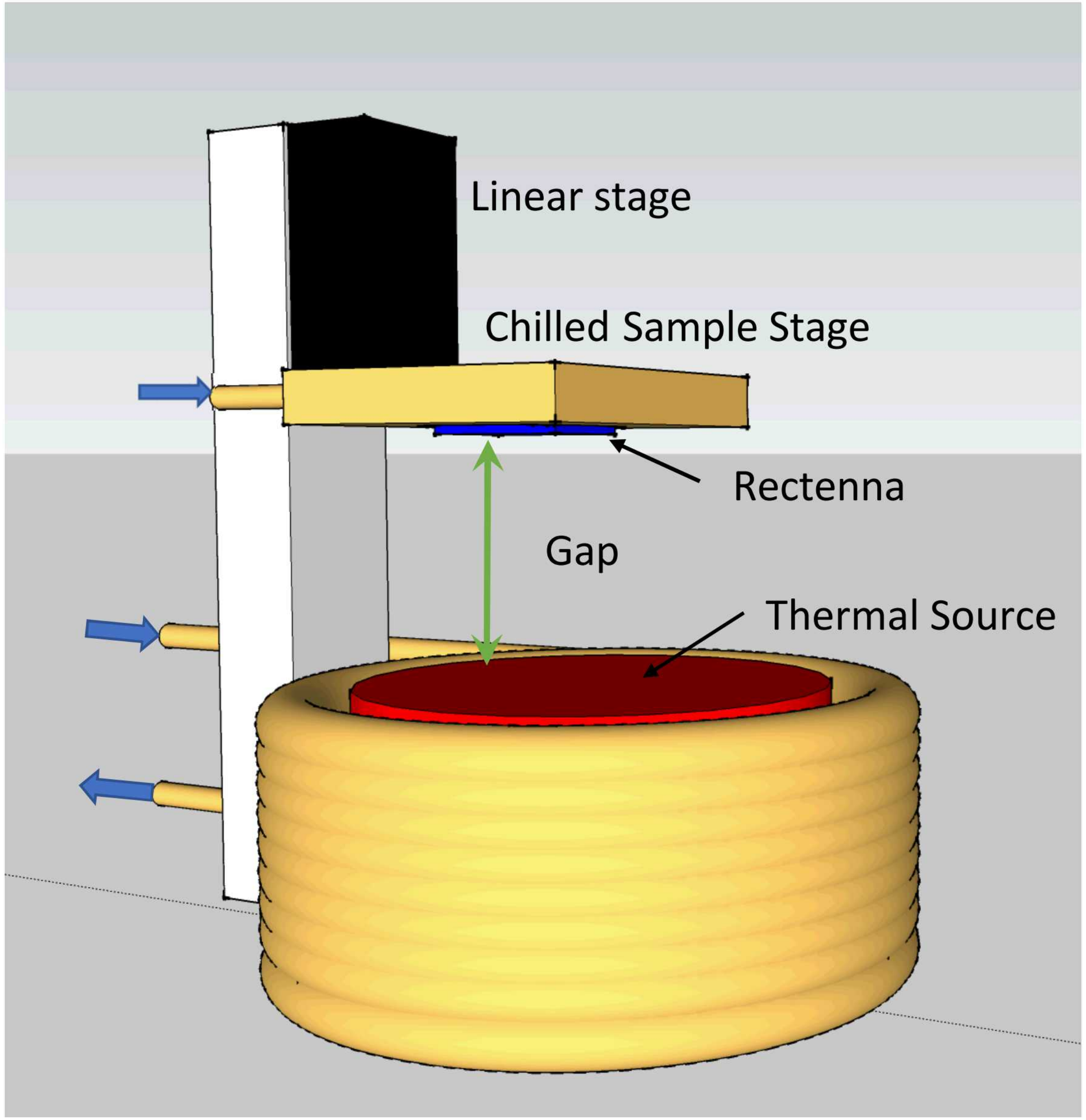
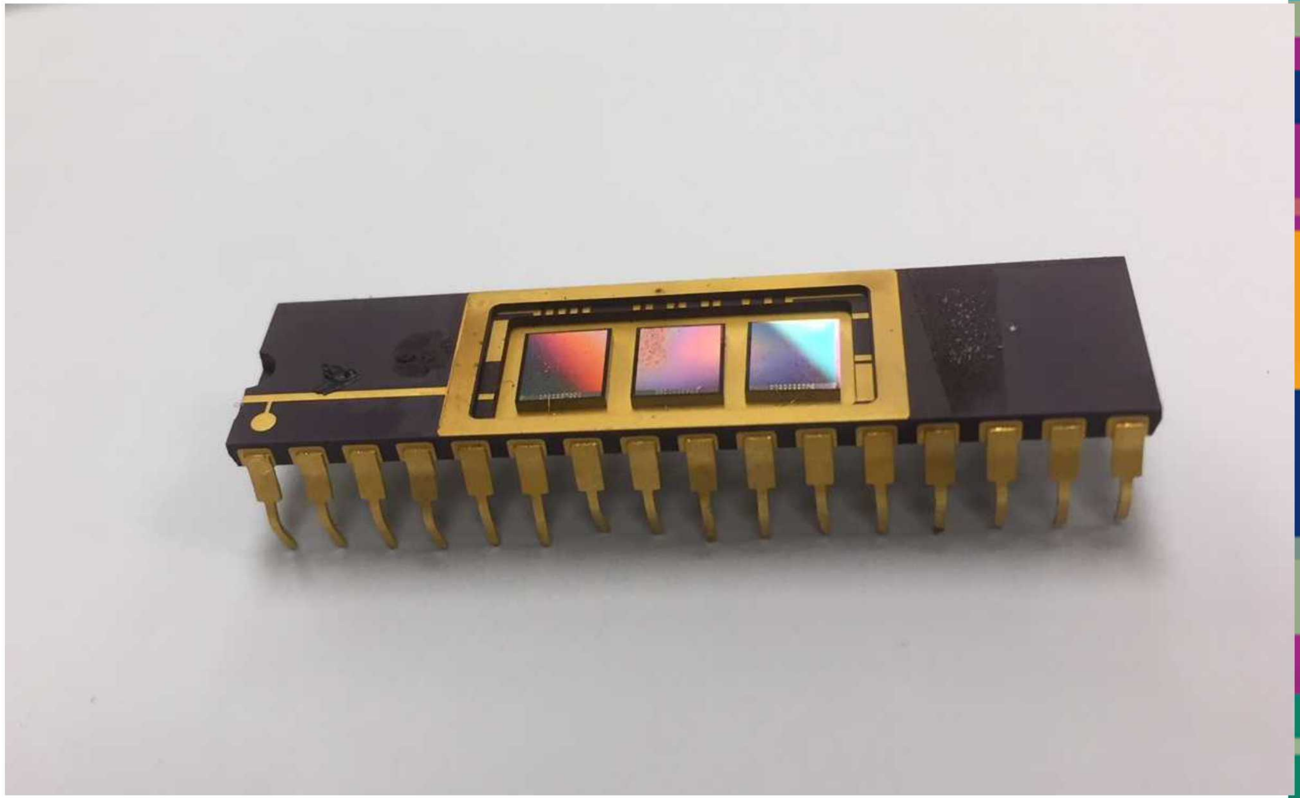


$$V = V_0 sin(2\pi f t)$$

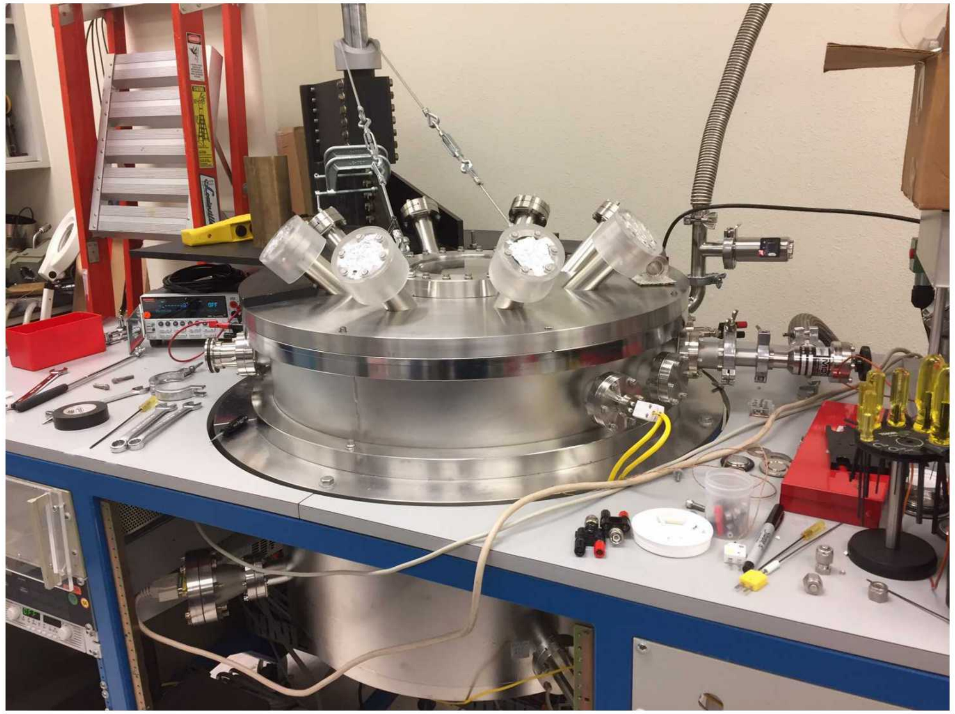
Radiometric thermal measurement



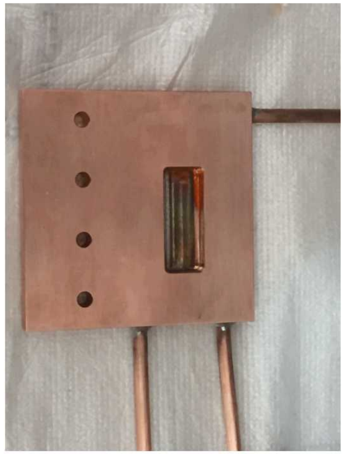


Vacuum Radiometric Setup

Vaccum setup

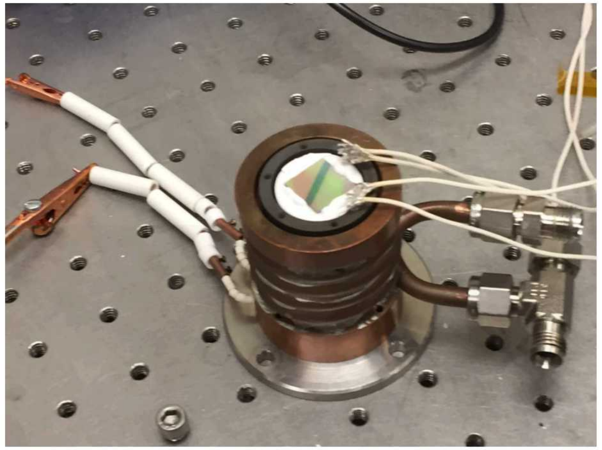


Water cooled sample

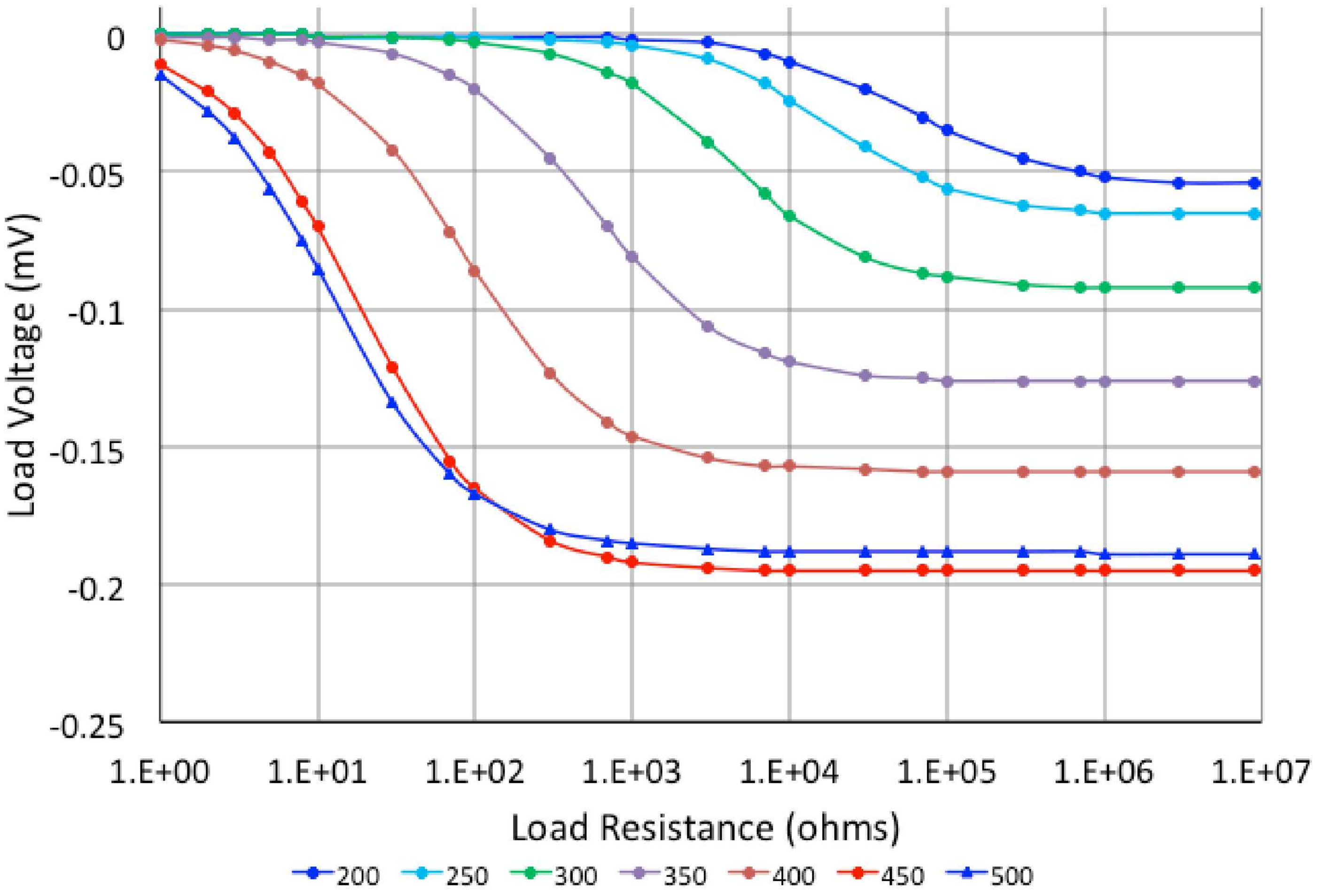


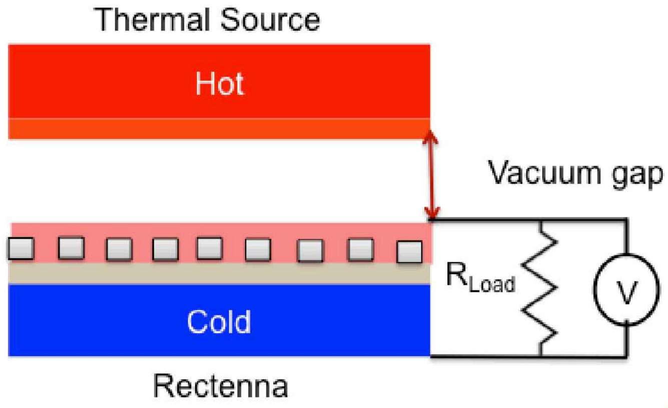
Packaged sample

Thermal source



Power generation





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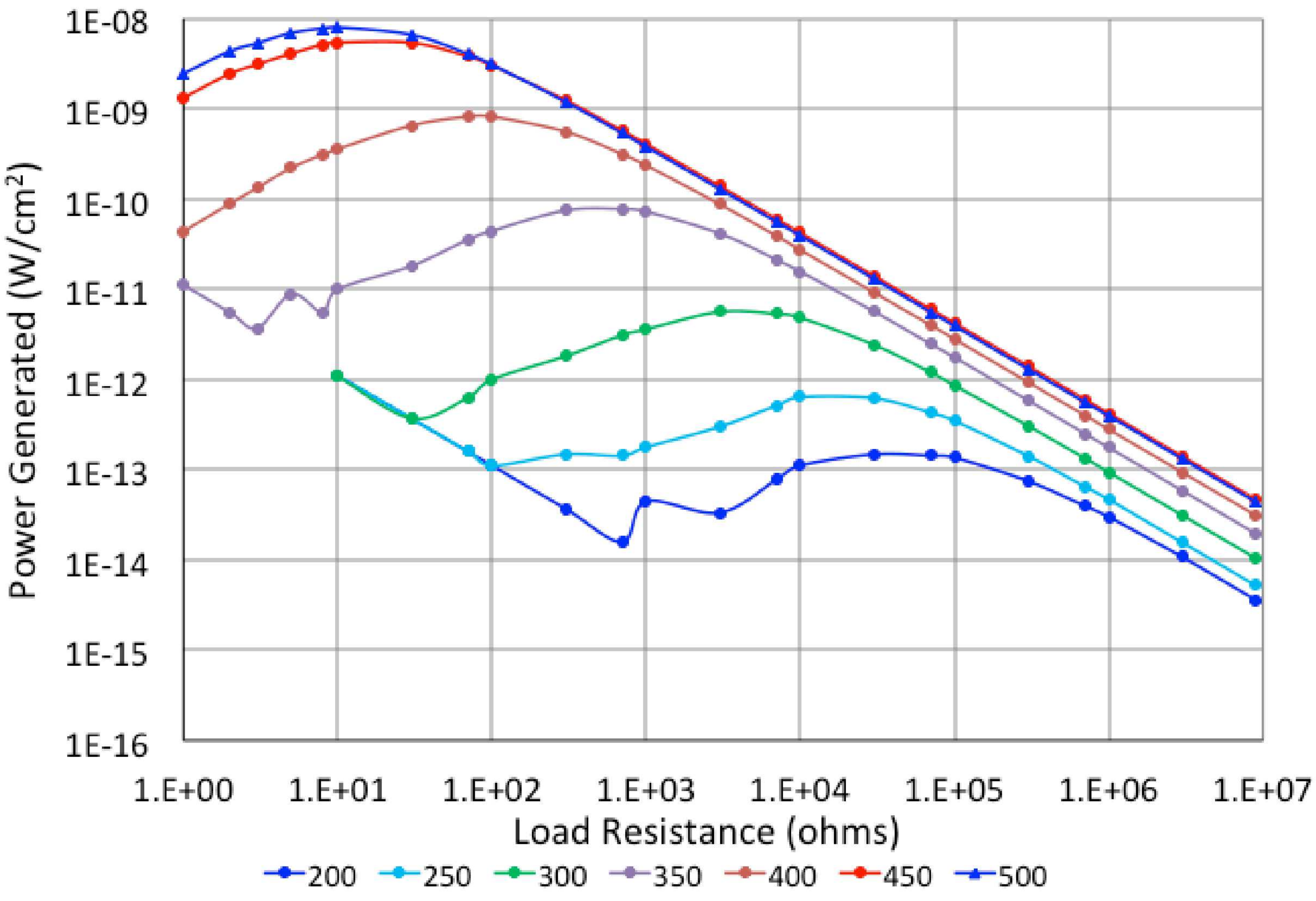
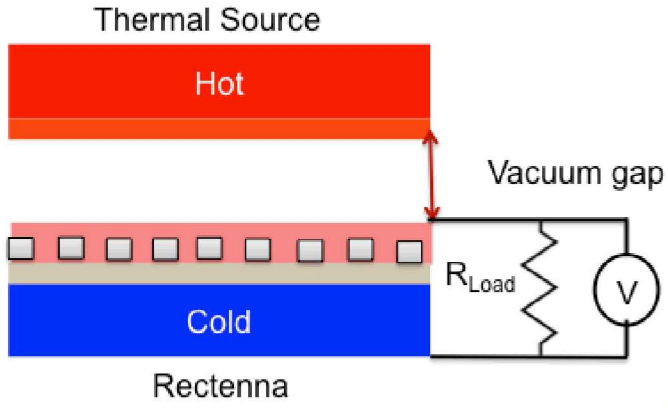
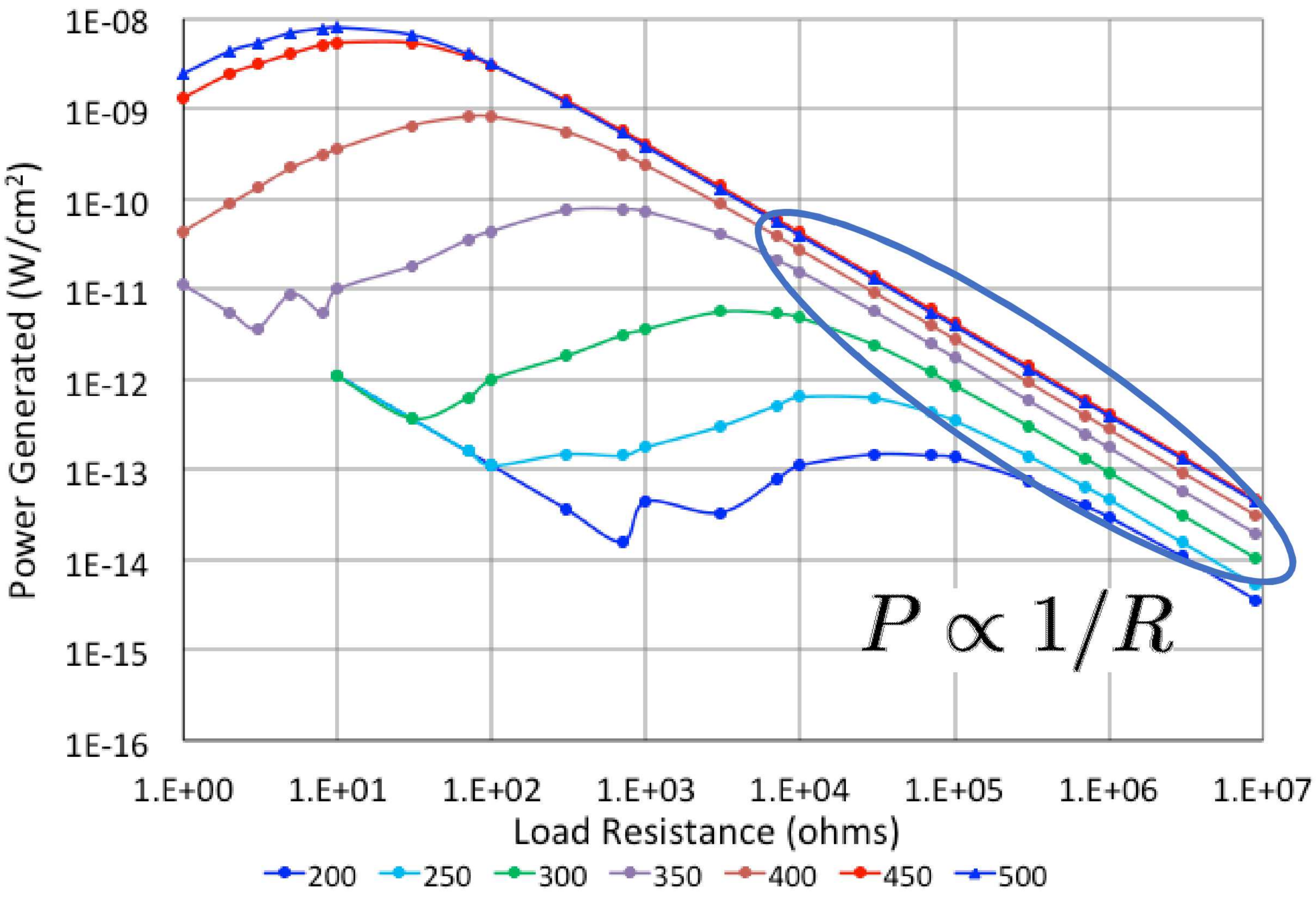
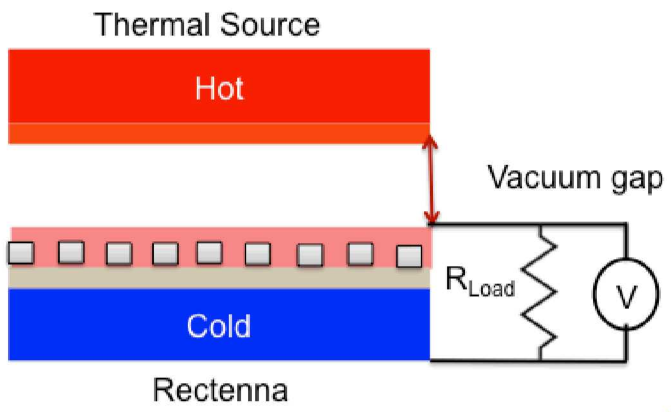


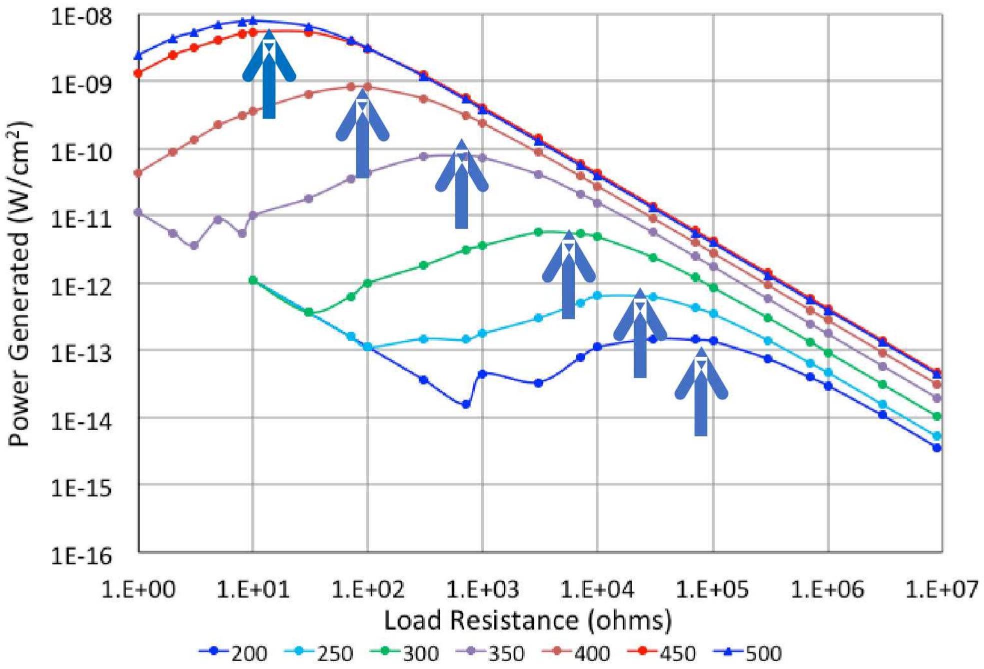


Power generation

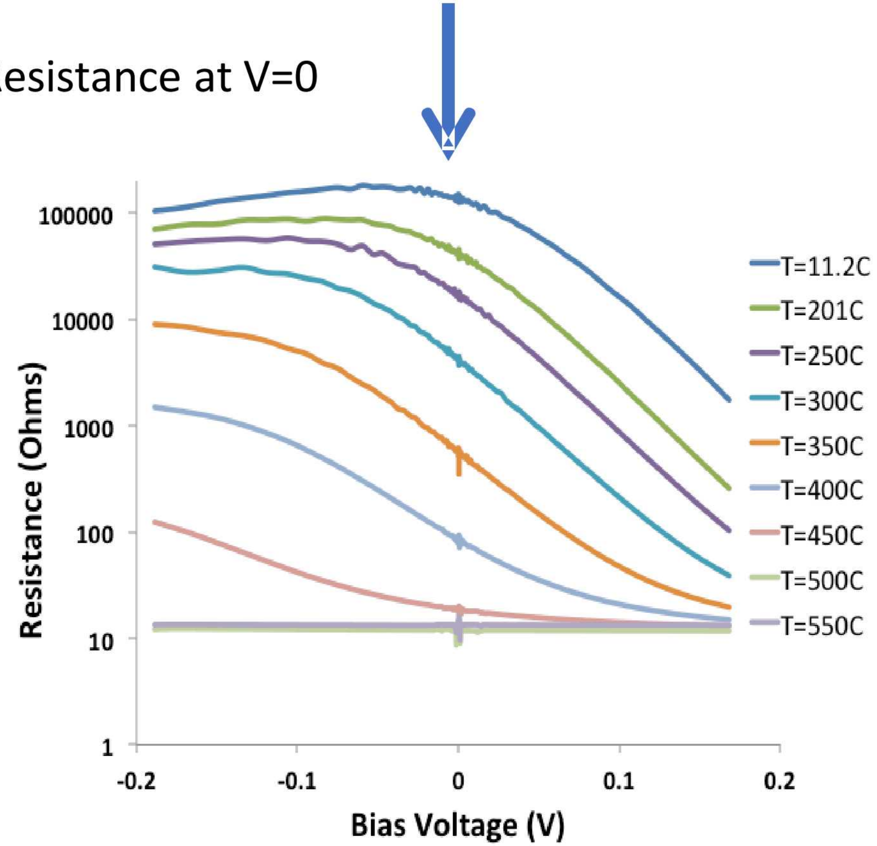




Impedance match



Resistance at V=0

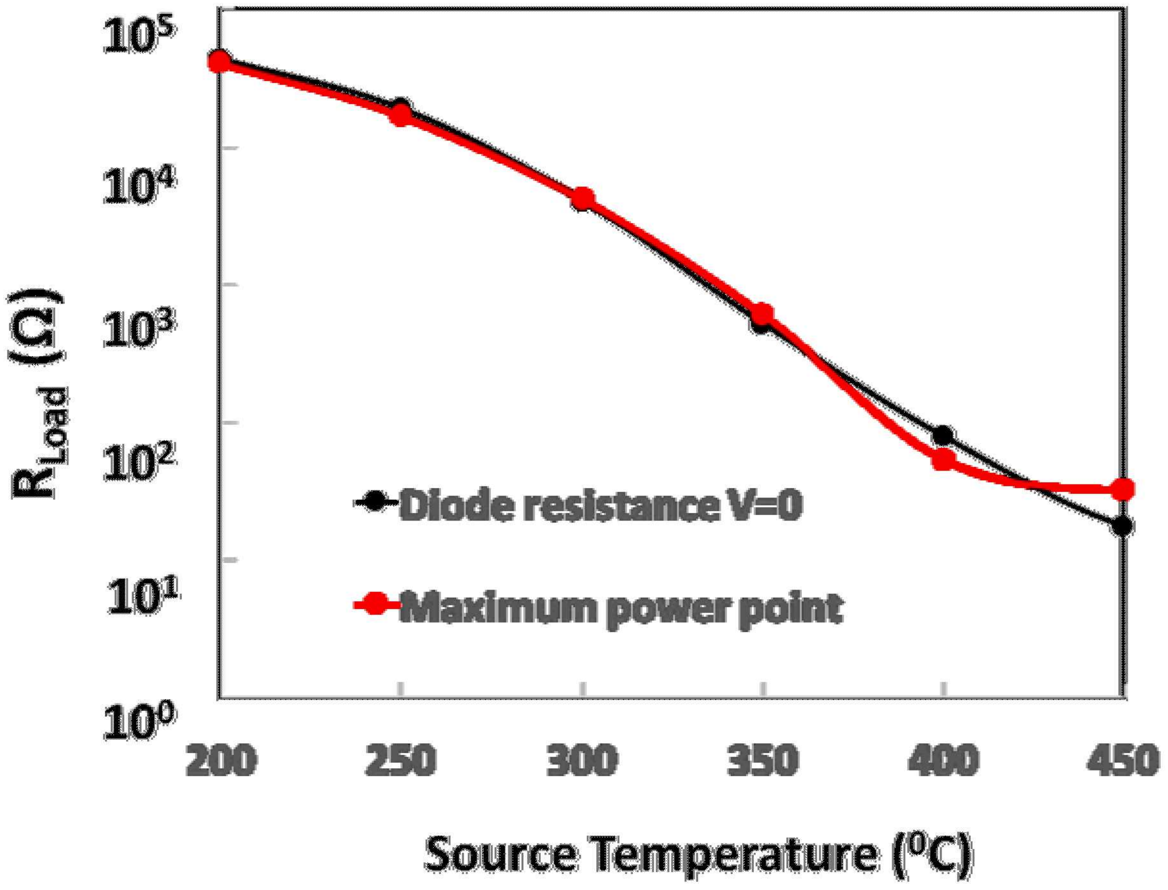


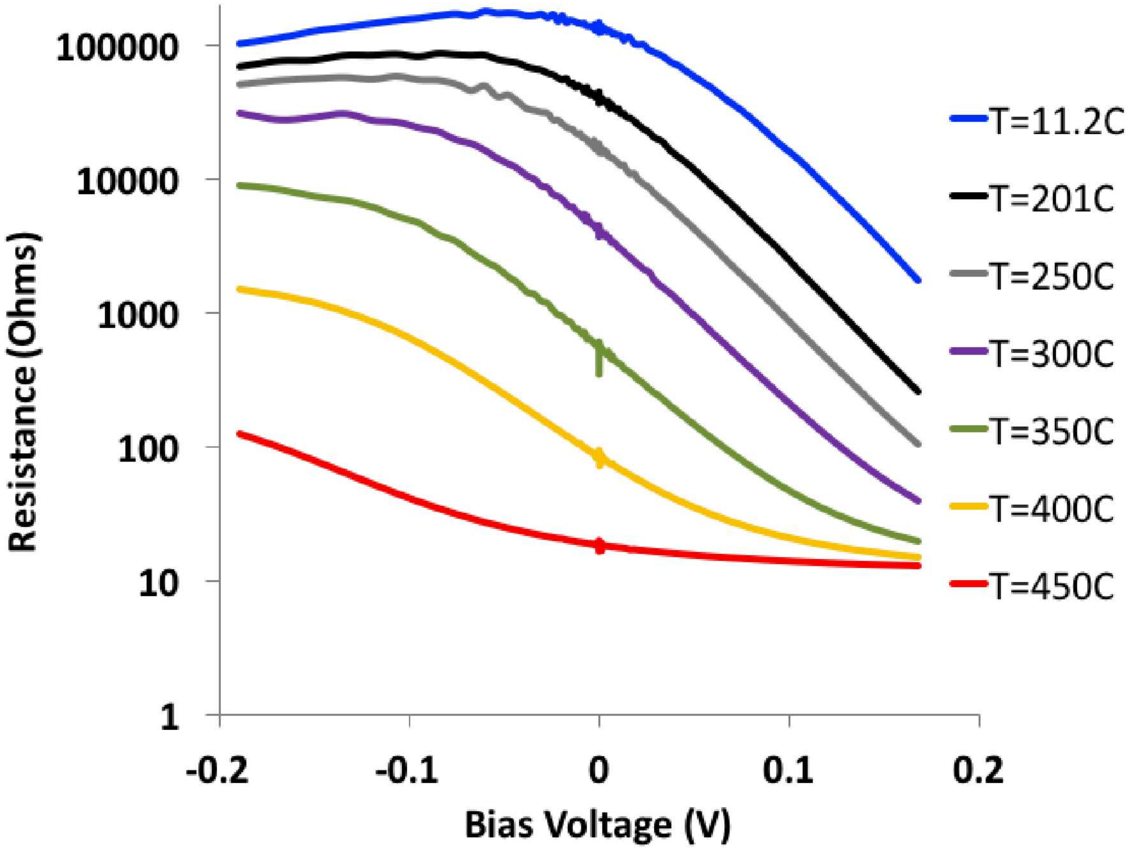
Diode resistance at V=0 is approximately the peak power load resistance

Wien's Law for Blackbody Spectral Radiance

$$\nu_{max} = T \cdot 58.8 \text{ GHz}/K \simeq 7.5\mu m \text{ for T} = 400\ ^0C$$

Impedance Match

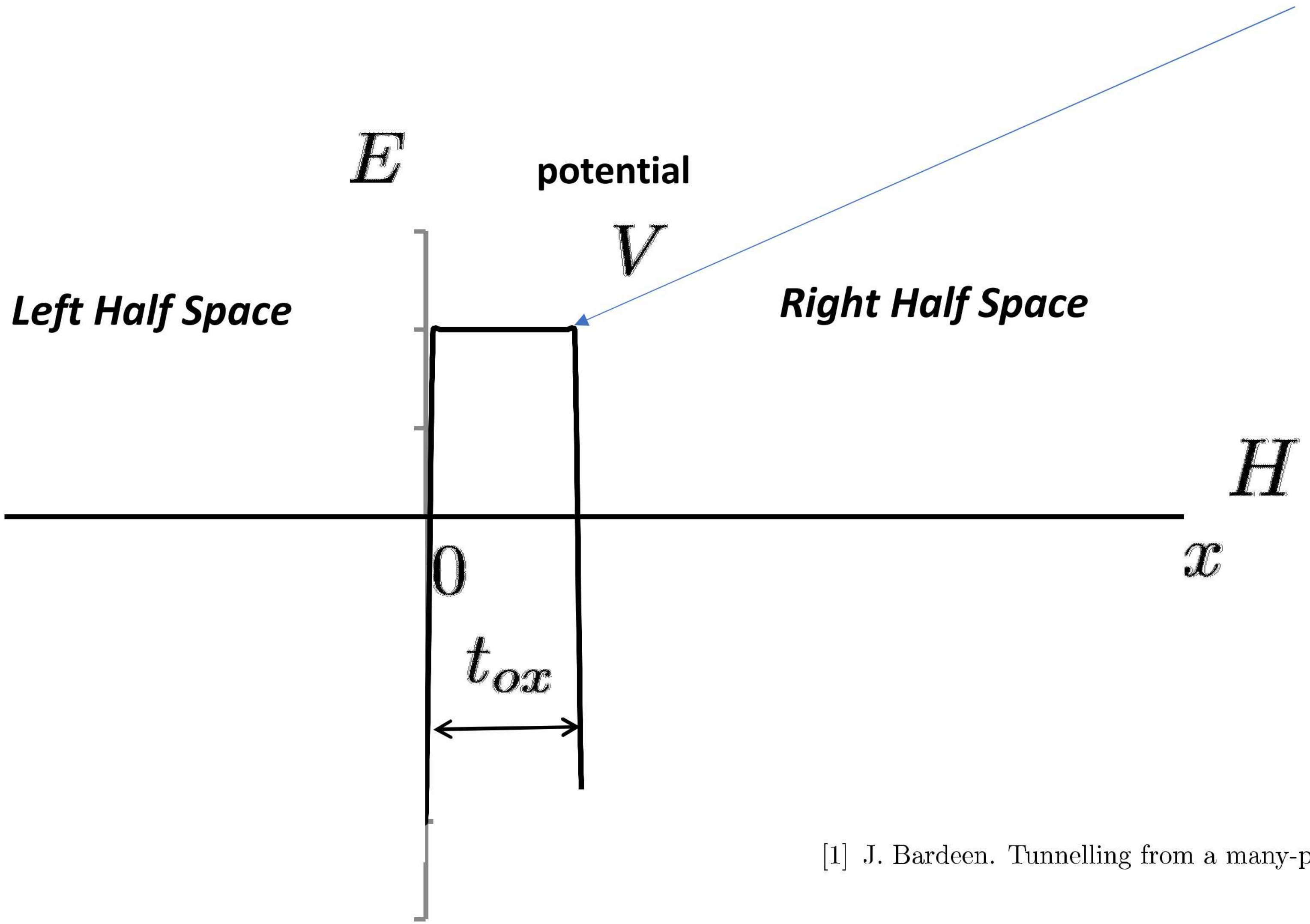




Power Generation Summary

- ***Demonstrated first direct electrical power generation from a broadband incoherent thermal source.***
- Power generation in 2^{nd} quadrant of IV.
- Impedance matching condition for rectenna.
  - Peak power transfer when antenna impedance matches load.
  - Peak electrical power versus load resistance shows peak power generation when load resistance matches measured diode resistance at zero volts.
- Measured voltage across load saturates.
- At 450^0C:
  - Power generated at peak ~ 8 nW/cm^2
  - Voltage across load saturates at -0.2 mV

Photon-assisted tunneling



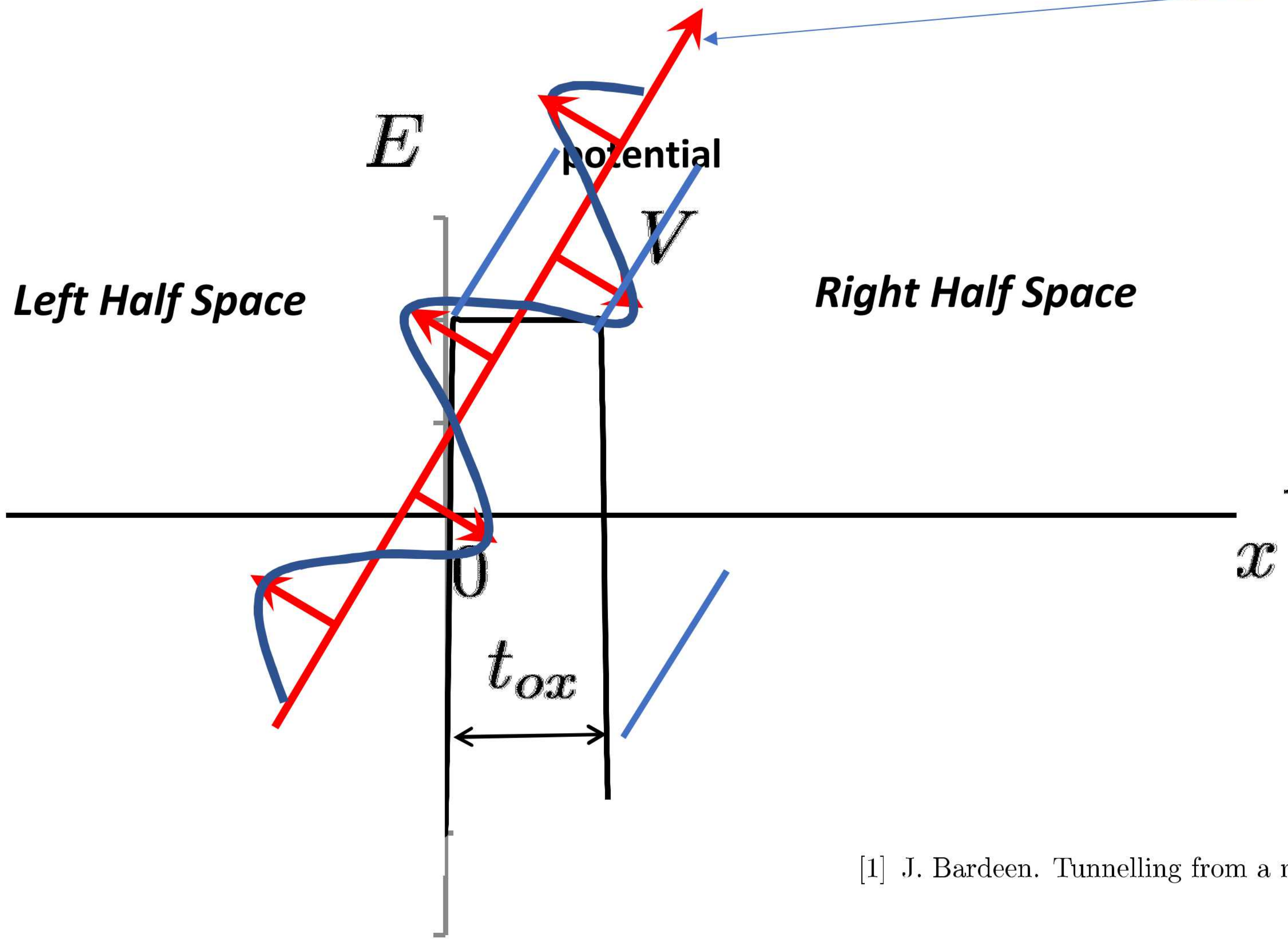
Transfer Hamiltonian

$$H = H_r + H_l + H_T(t)$$

Proposed by Bardeen

[1] J. Bardeen. Tunnelling from a many-particle point of view. *Phys. Rev. Lett.*, 6:57–59, Jan 1961.

Photon-assisted tunneling



Electromagnetic field

Transfer Hamiltonian

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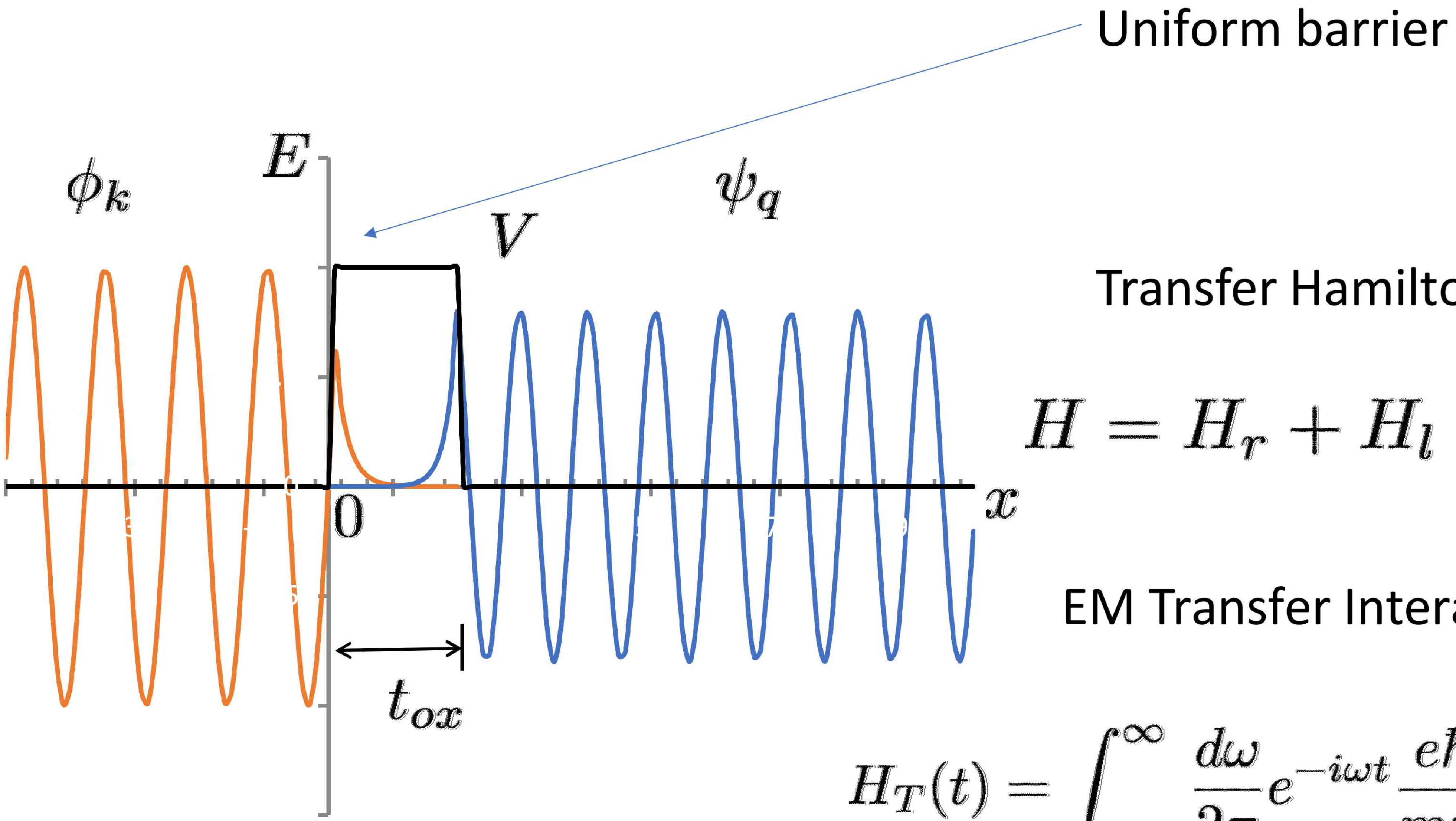

Transfer Hamiltonian

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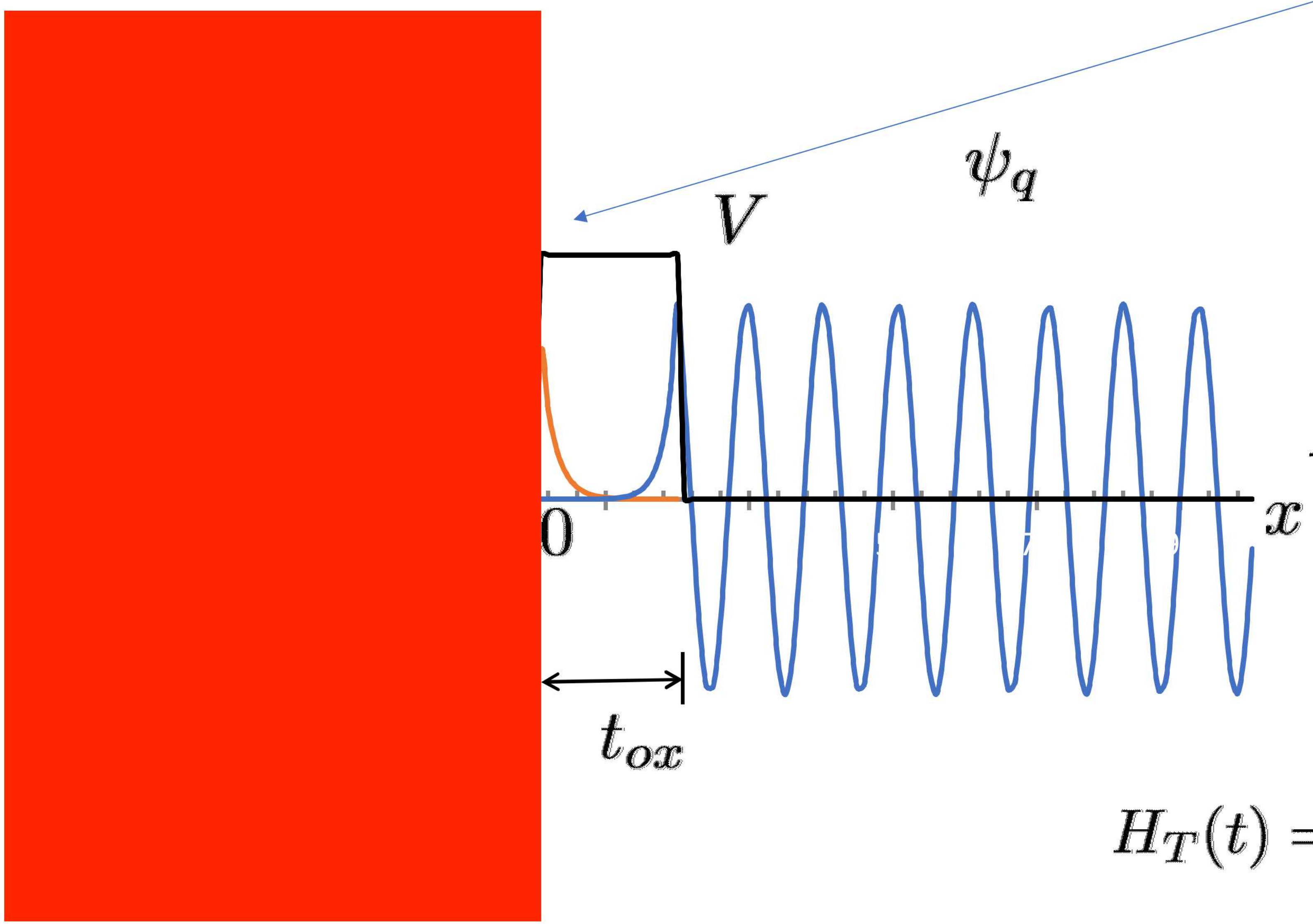
EM Transfer Interaction

$$H_T(t) = \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} e^{-i\omega t} \frac{e\hbar}{m\omega} \mathbf{E}(\omega) \cdot \nabla$$

Photon-assisted tunneling

Uniform barrier



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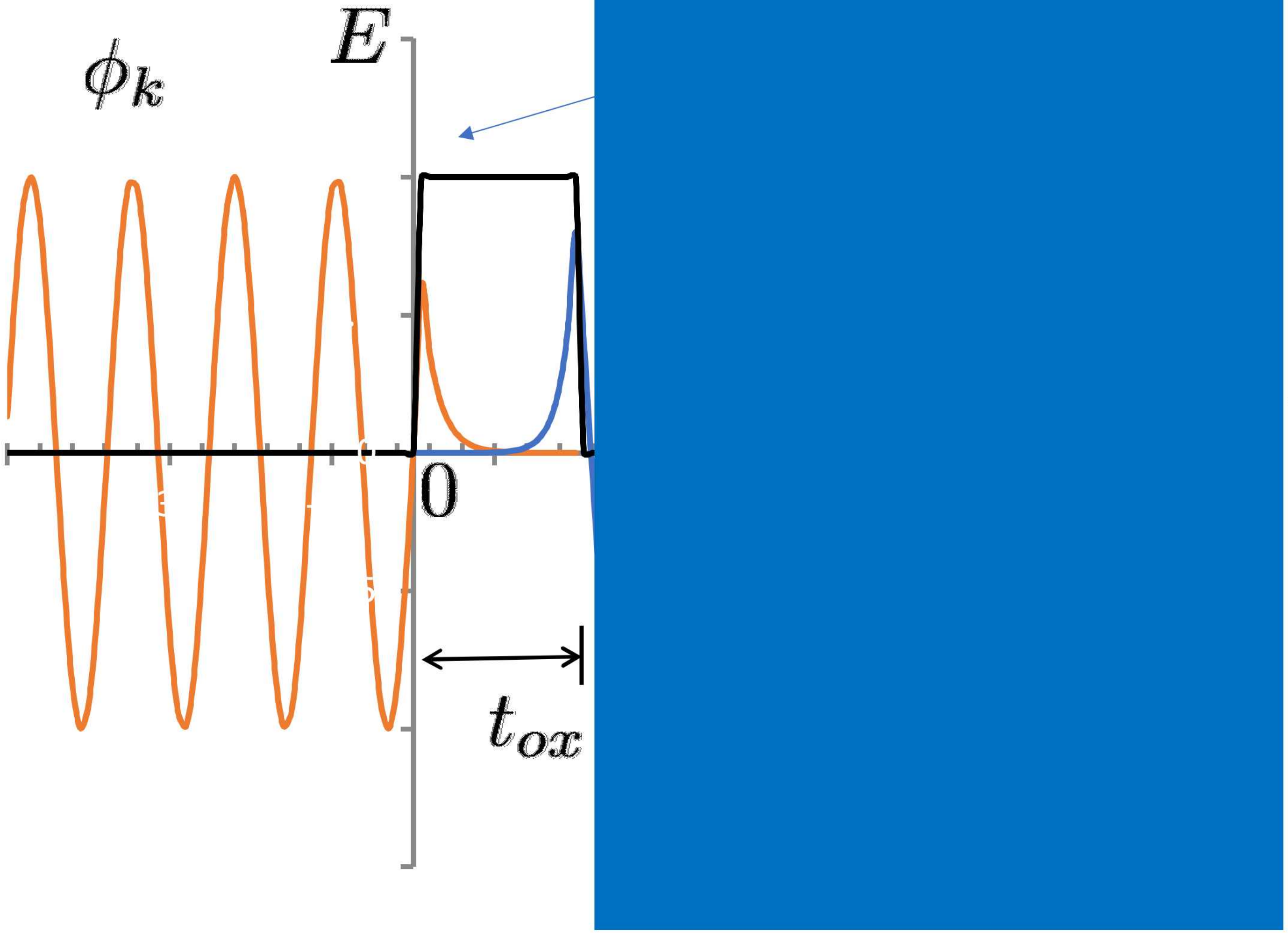

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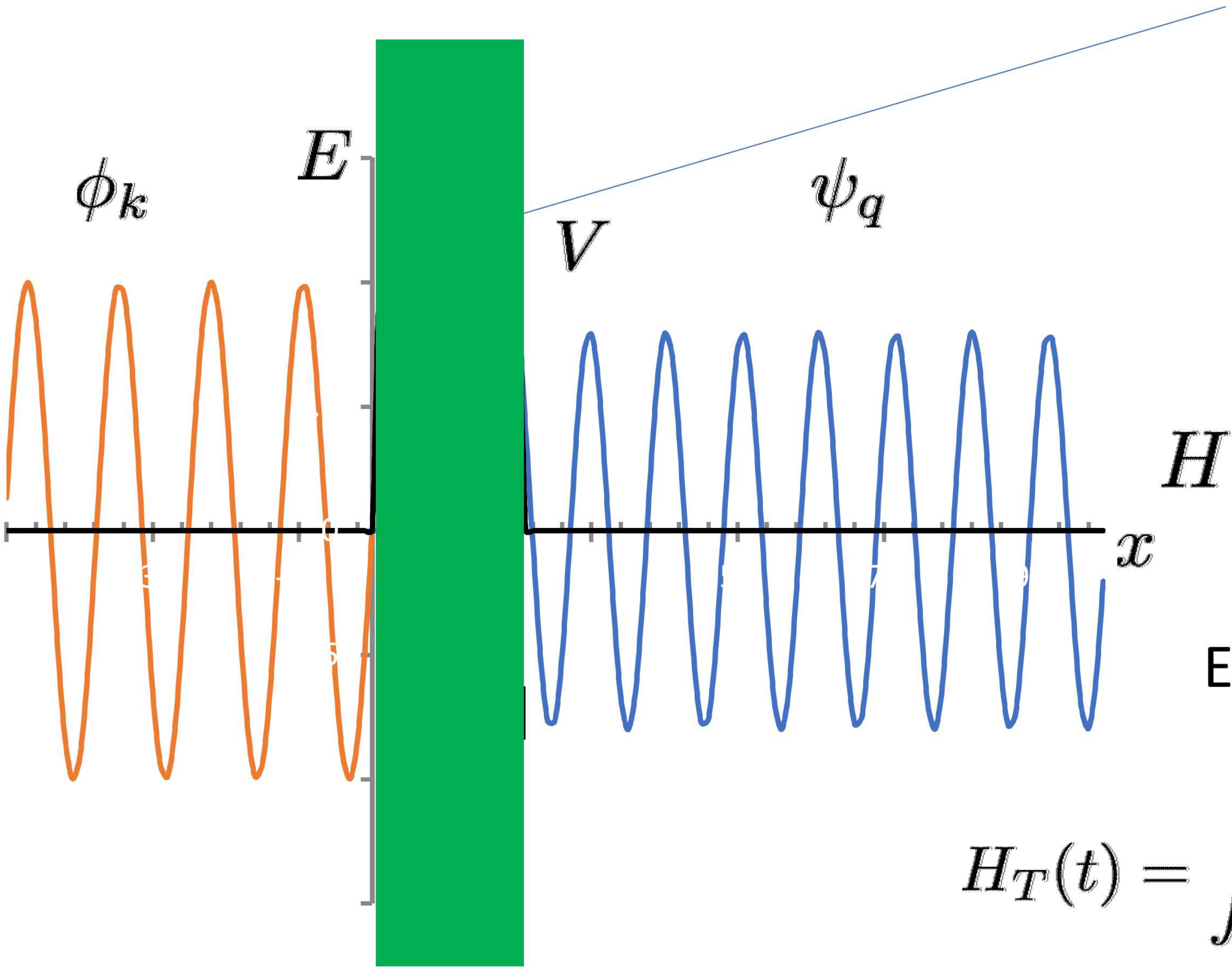

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Density matrix expansion

Equation of Motion

$$i\hbar\frac{\partial\rho_{nm}}{\partial t} = (E_n - E_m)\rho_{nm} + \sum_{n'm'}\left(< n|H_T n' > \delta_{m,m'} - < m' H_T^*|m > \delta_{n,n'}\right)\rho_{n'm'}$$

<u>Perturbative Transfer Interaction</u>

$$H_T(t) \rightarrow \lambda H_T(t))$$

$$\rho_{nm} = \rho_{nm}^{(0)} + \lambda\rho_{nm}^{(1)}(t) + \lambda^2\rho_{nm}^{(2)}(t) + \lambda^3\rho_{nm}^{(3)}(t)\ldots,$$

[1] P. S. Davids and J. Shank. Density matrix approach to photon-assisted tunneling in the transfer hamiltonian formalism. *Phys. Rev. B*, 97:075411, Feb 2018.

Non-linear Current and Conductance

$$I = -i\frac{2e}{\hbar}\sum_{nm}\int_{-\infty}^{\infty}\frac{d\omega}{2\pi}\tilde{V}_{m,n}(\omega)\ \tilde{\rho}_{nm}(\omega).$$

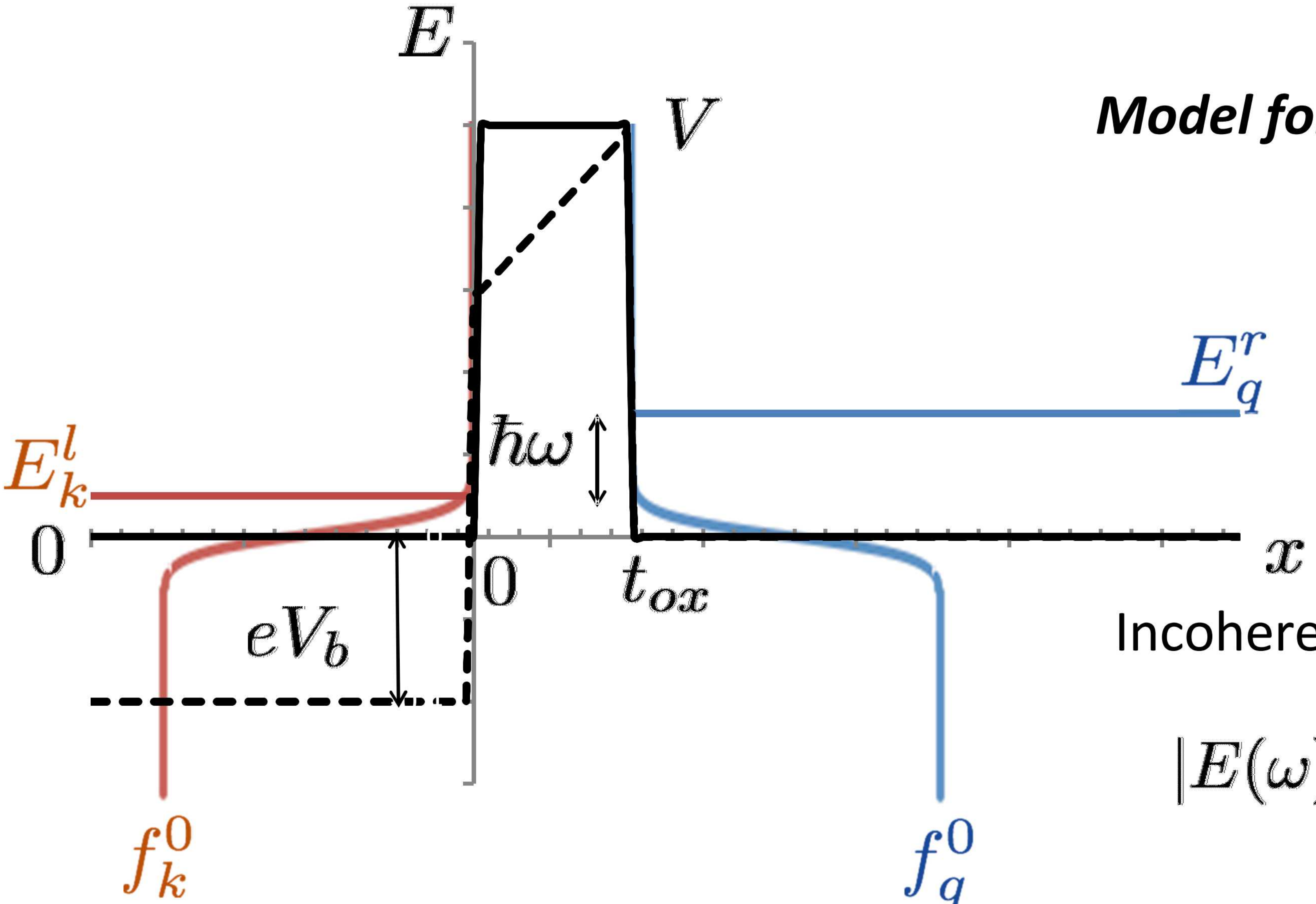
$$\tilde{V}_{m,n'}(\omega) = \frac{e\hbar}{m\omega}\int d\mathbf{x}\ \mathbf{E}^*(\omega)\cdot\left(\phi_m^*(\nabla\phi_{n'}\right)$$

First order term is Bardeen tunnel current

↙

$$I = I^{(0)} + \lambda I^{(1)} + \lambda^2 I^{(2)} + \lambda^3 I^{(3)} \ldots$$

Photon-assisted tunneling

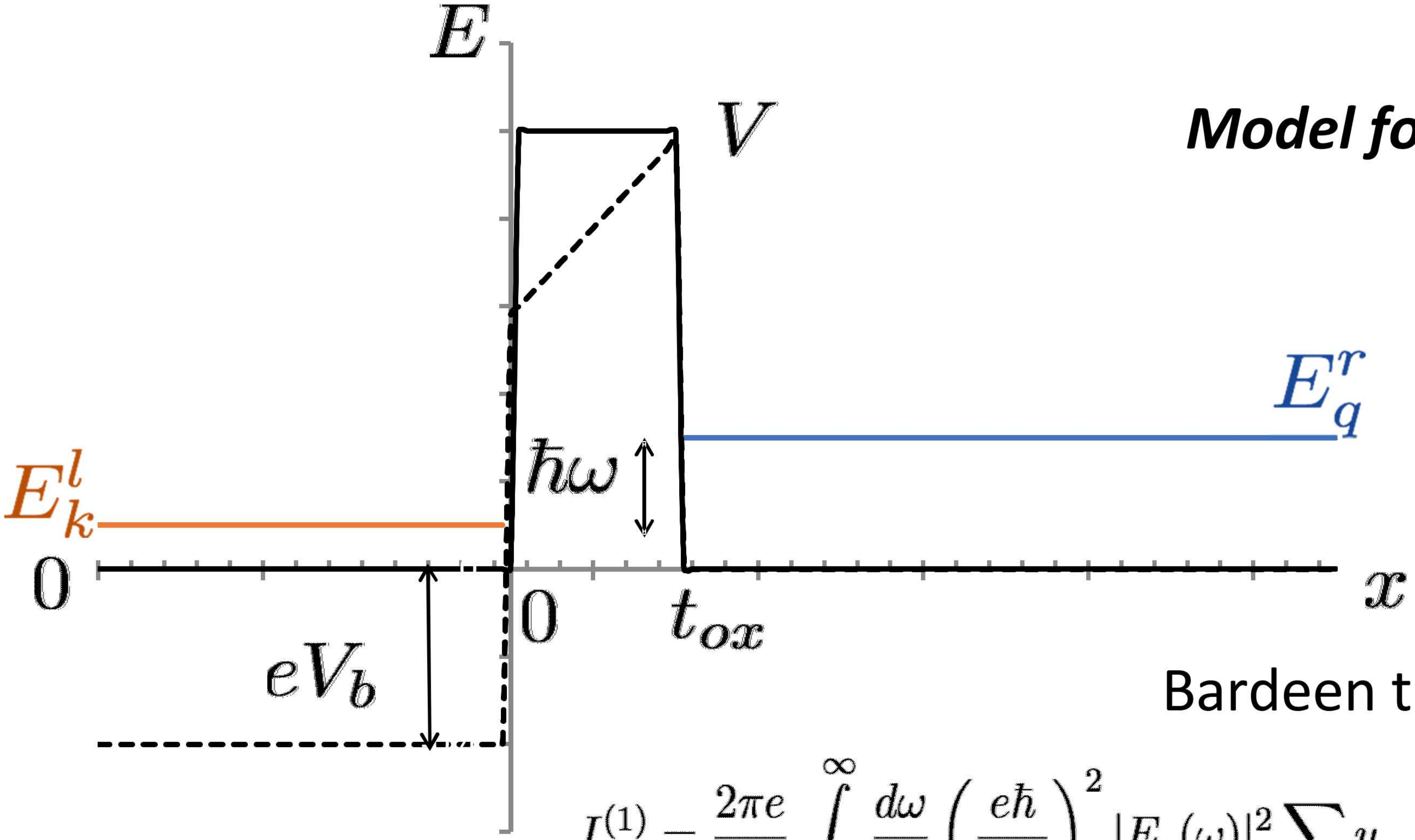


Model for n+ MOS tunnel diode

Incoherent Blackbody field in gap

$$|E(\omega)|^2 = 2Z_0 M_\nu^0(T)$$

Photon-assisted tunneling



Model for n+ MOS tunnel diode

Bardeen tunneling current

$$I^{(1)} = \frac{2\pi e}{\hbar} \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} \left(\frac{e\hbar}{m\omega}\right)^2 |E_z(\omega)|^2 \sum_{nm} u_{mn} u_{nm} (f_m - f_n) \delta(\hbar\omega - E_n + E_m),$$

First order PAT current

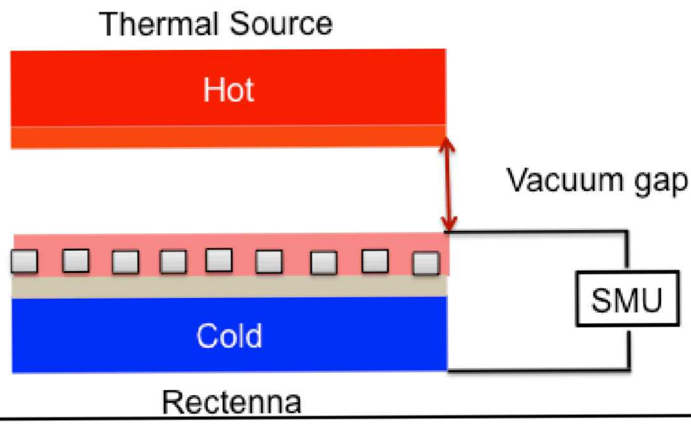
- First order expansion of single particle density matrix in Bardeen's transfer Hamiltonian approach.
- Photon-assisted tunnel current for partially coherent thermal source.

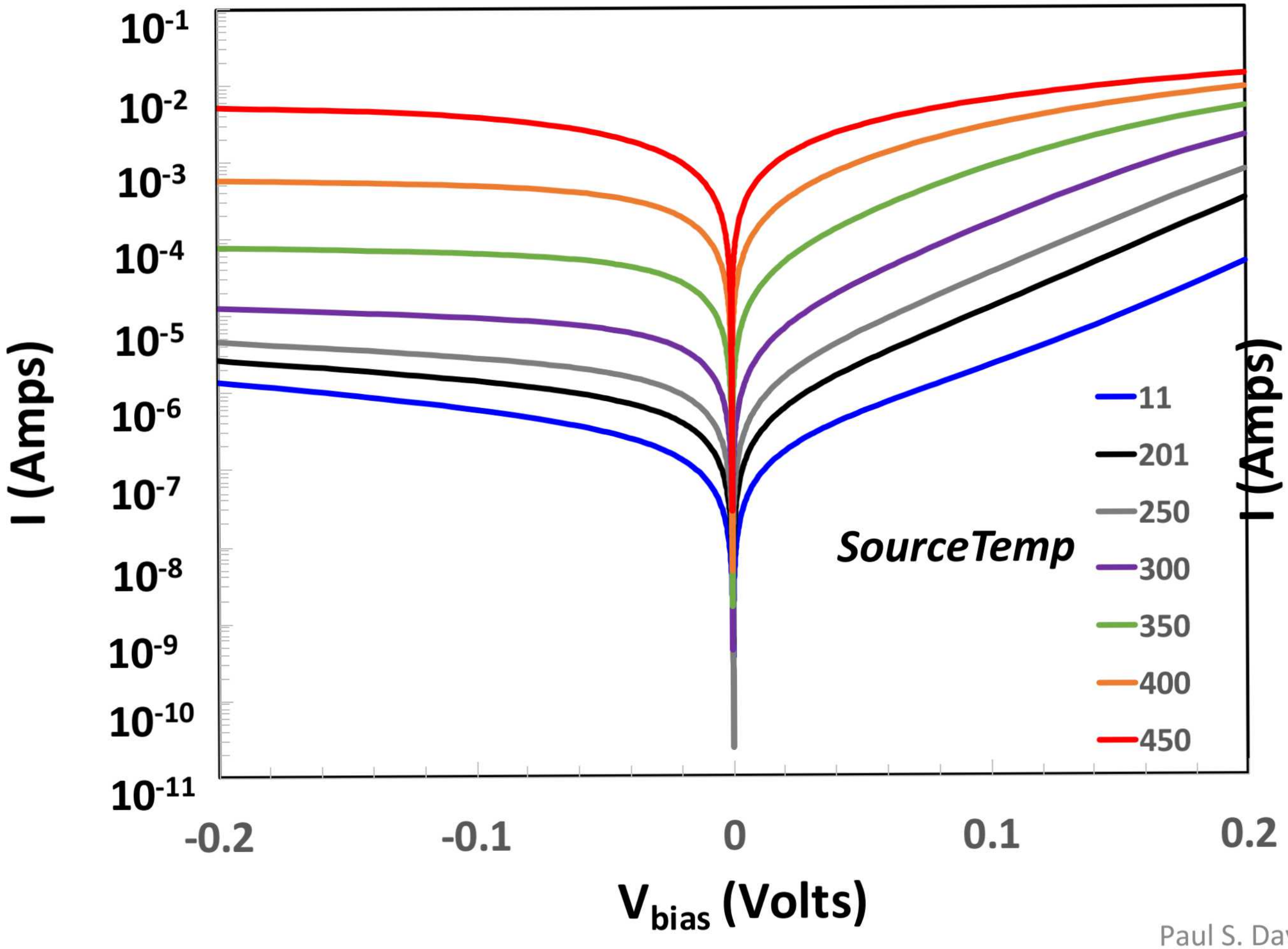
$$J^{(1)} = \frac{4\pi e m_e}{h^3 \beta^2} \left(\frac{m_r m_l}{m_{ox}^2} \right) \int_0^\infty \frac{d\omega}{2\pi} \left(\frac{e t_{ox}}{\hbar\omega} \right)^2 |E(\omega)|^2 \mathcal{T}(\omega),$$

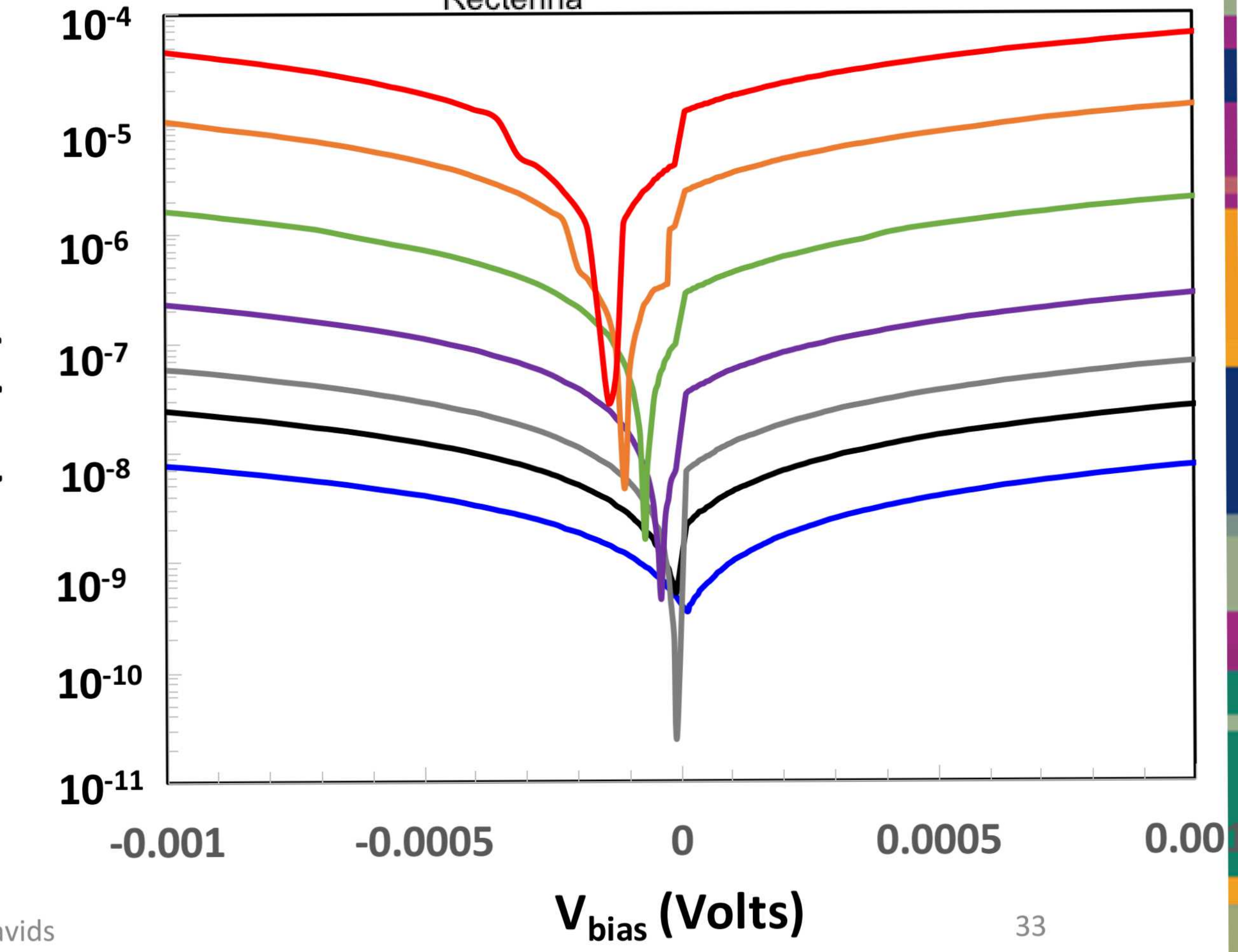
$$\mathcal{T}(\omega) = \beta \int dE_l \; t(E_l, E_l + \hbar\omega) \log\left[\frac{1+\exp(-\beta E_l)}{1+\exp(-\beta(E_l+\hbar\omega))} \right] + (\omega \to -\omega)$$

Use first order current expression to predict Photo-assisted tunneling short circuit current

IV under thermal illumination

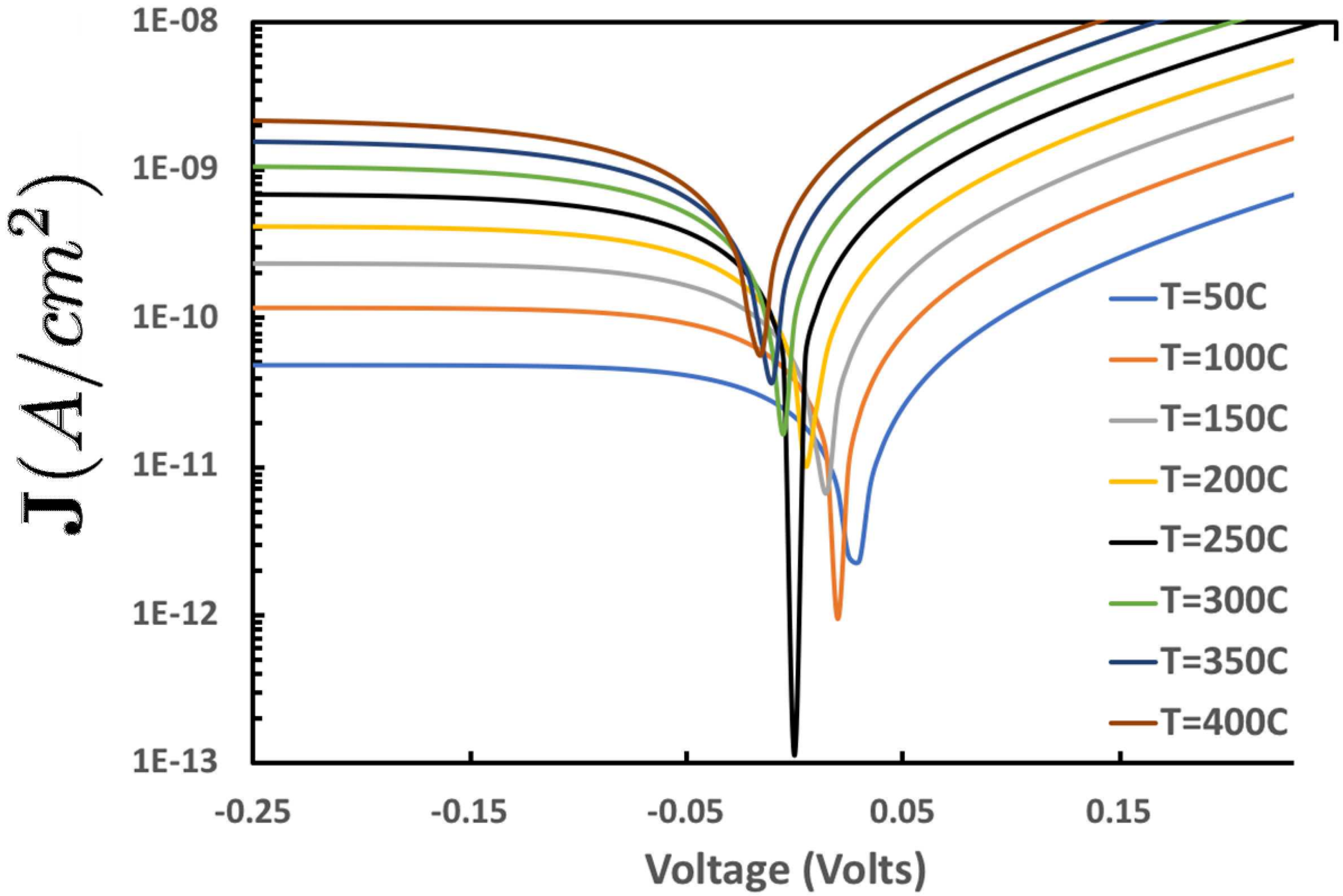


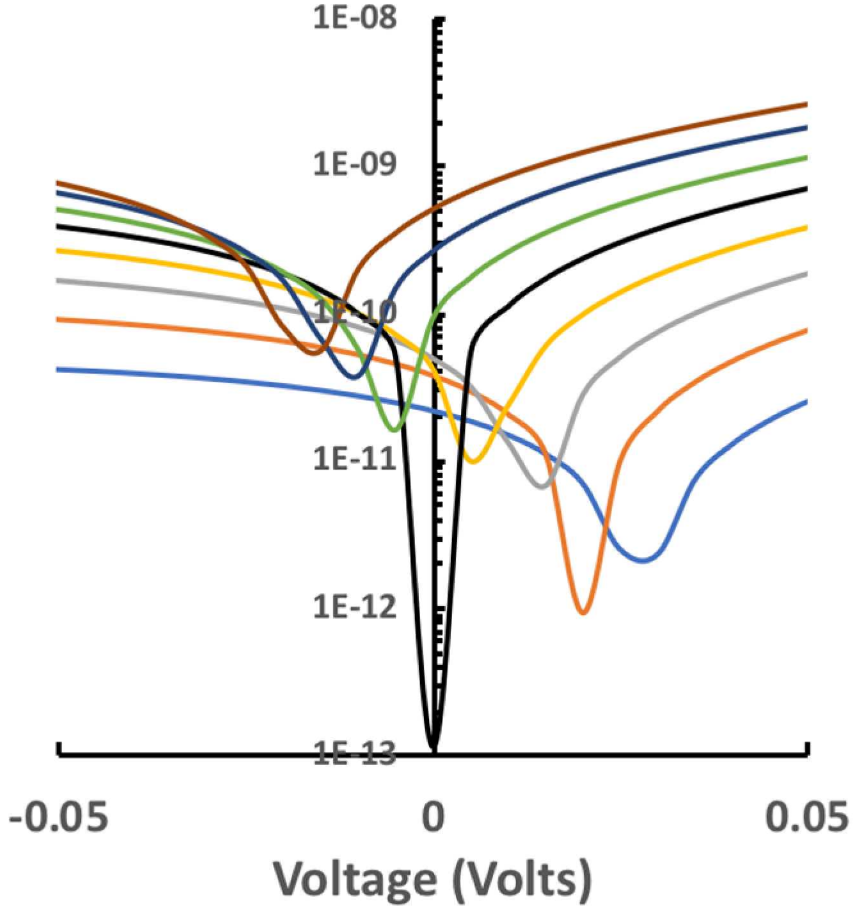




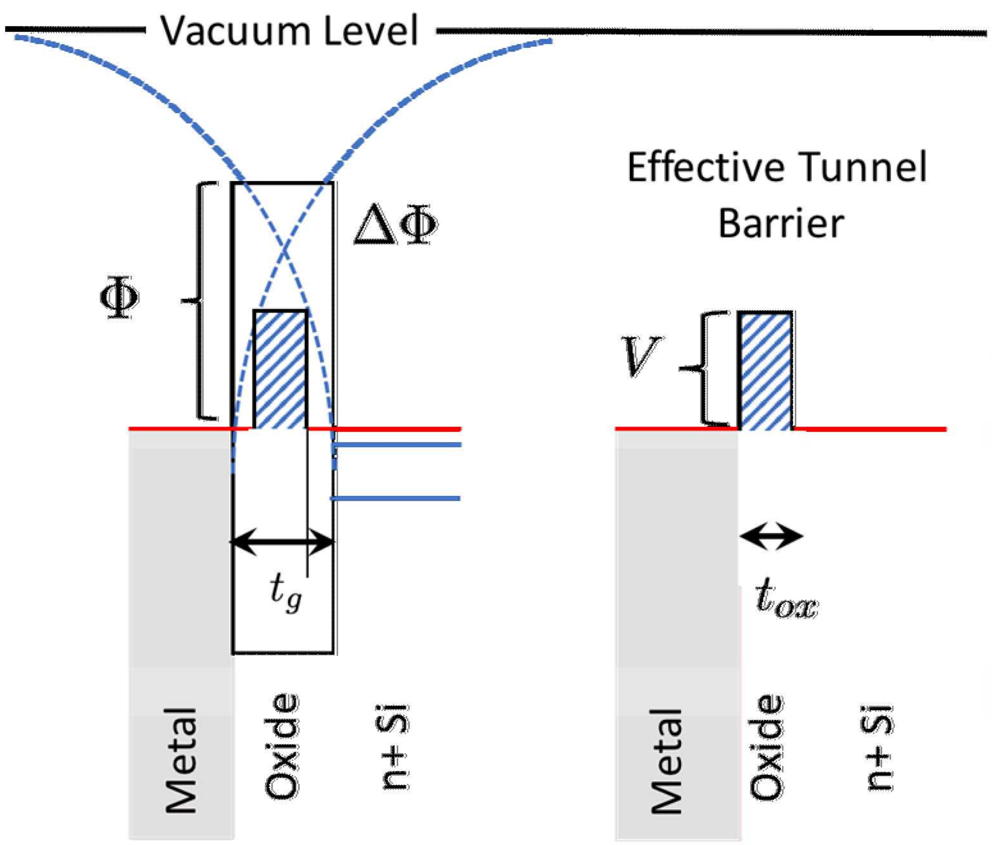
Photon-assisted Tunneling Model

MOS parameters: Barrier height 1.65, tox= 3.5 nm , wavelength = 7.5 um , bandwidth 1THz





Photon Assisted Short Circuit Current



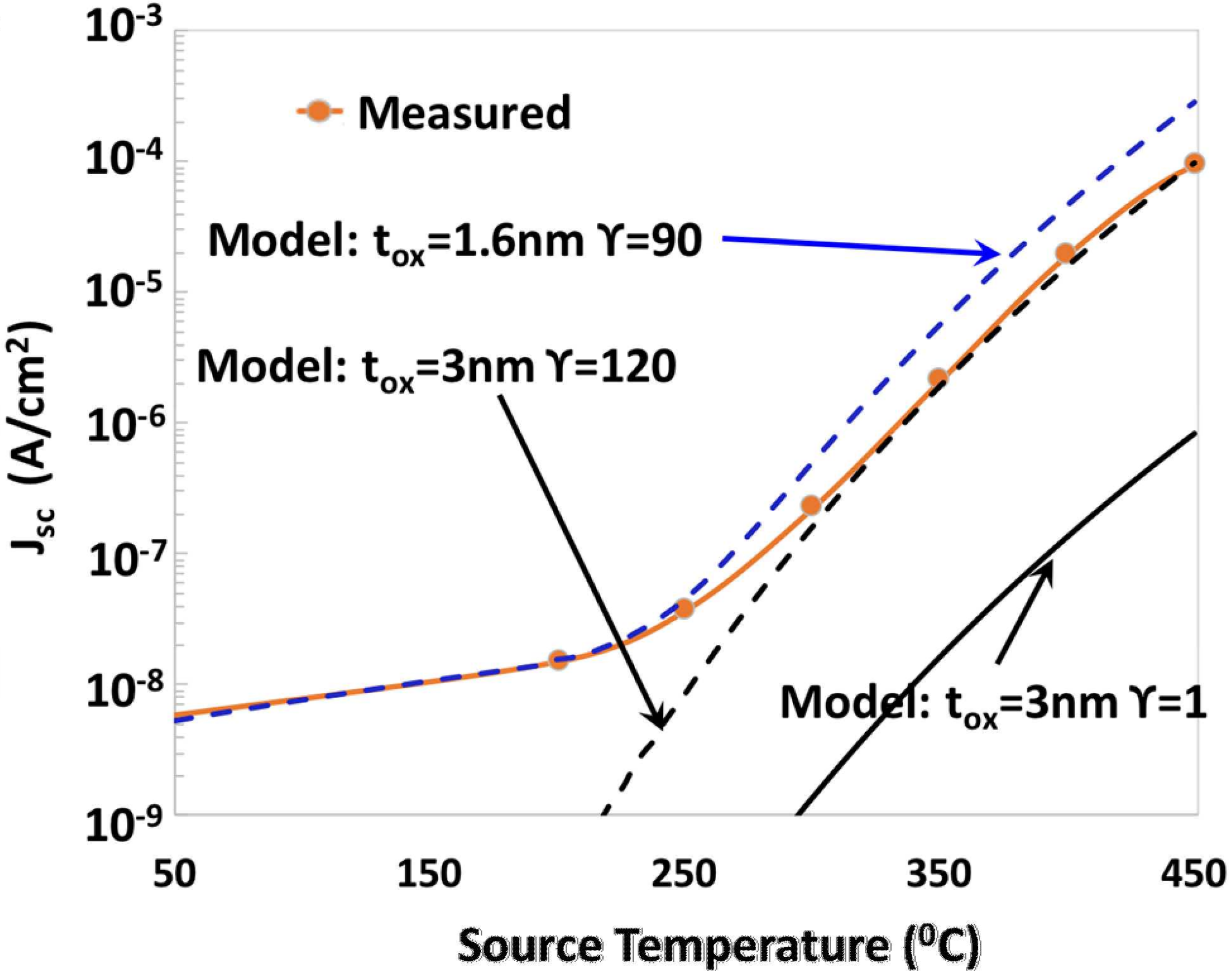
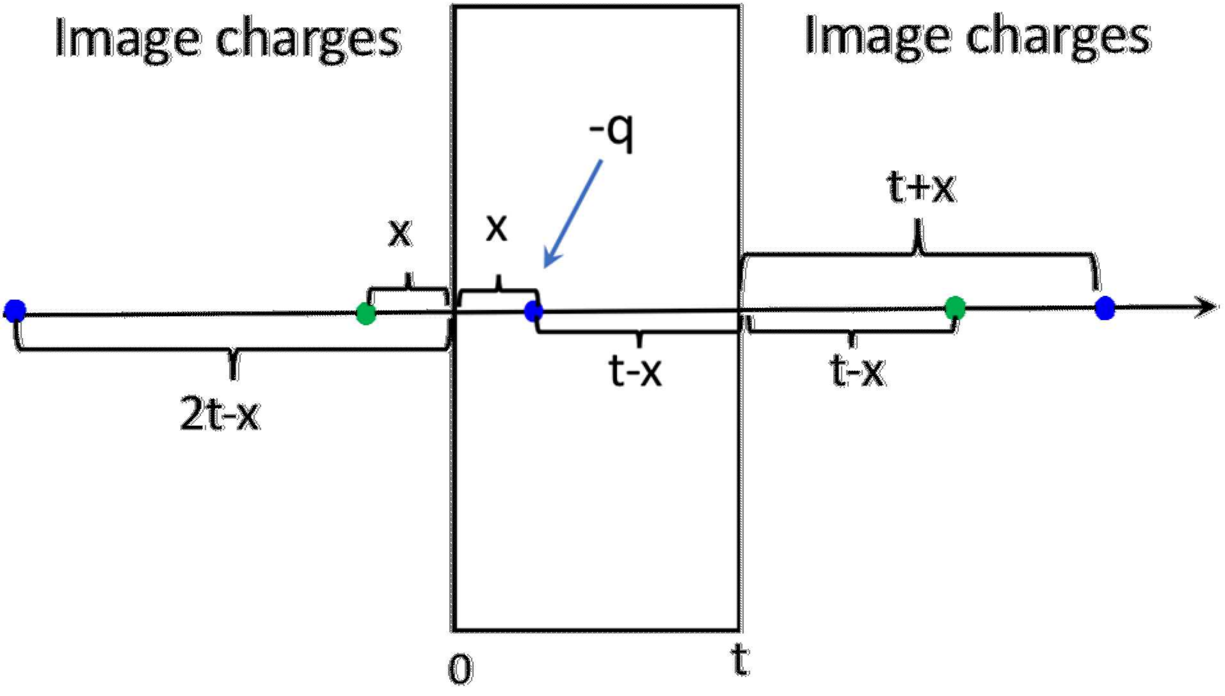
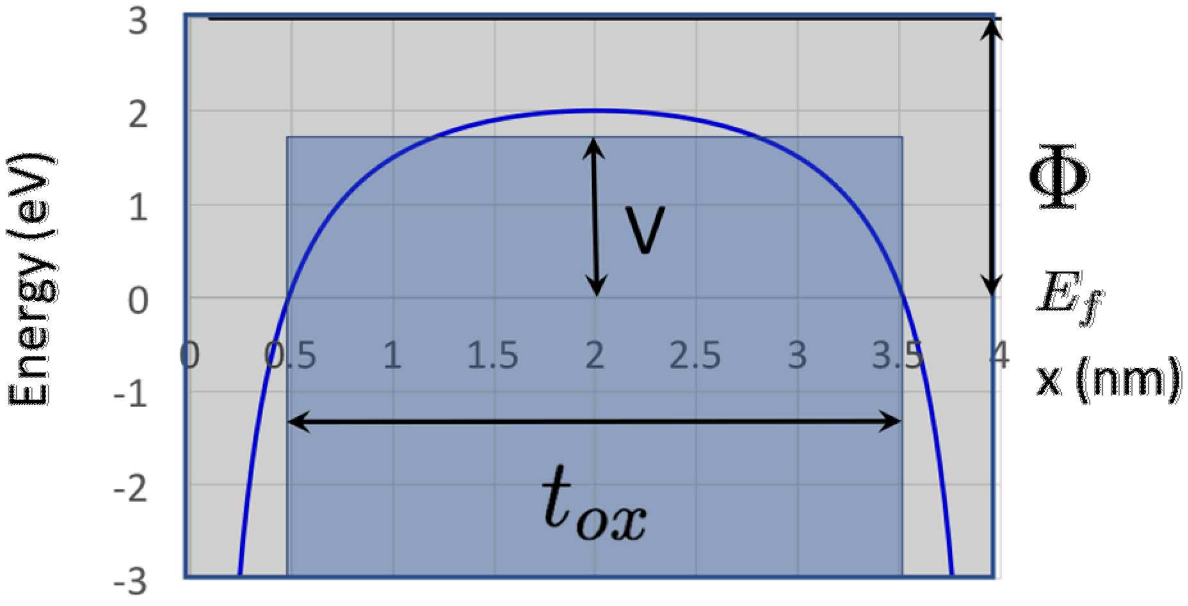


Image force barrier lowering





$$J^{(1)} = AT^2 \left(\frac{m_r m_l}{m_{ox}^2} \right) 2Z_0 \int_{\nu_{min}}^{\nu_{max}} d\nu (1 - R^2) \gamma^2 \left(\frac{e t_{ox}}{h\nu} \right)^2 M_\nu^0(T)\, \mathcal{T}(\nu),$$

Photon-assisted Tunneling Summary

- Developed photon-assisted tunneling model to explain current-voltage characteristics of metasurface coupled tunnel diode rectifier.
- First principle tunneling model based on many-body density matrix expansion.
    - No WKB approximation
    - 1^{st} order term is Bardeen tunneling expression.
    - Uniform barrier model allows for exact rectified current expression.
    - Non-linear expansion of current as a function of transverse electric field.
- Resonant antenna and ENZ field confinement & enhancement in tunnel barrier gives rise to large tunneling photocurrent.
- Included Effects:
    - Image potential lowering of barrier (effective barrier height and width)
    - Field enhancement factor fit to measured IV data.

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